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PLATE TECTONICS AND THE DISCRIMINATION OF UNDERGROUND EXPLOSIONS FROM EARTHQUAKES

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13. ABSTRACT

The following work was undertaken during this contract:

During the life of this contract (1 September 1971 to 30 September 1975), research topics under each of the eight line items have been investigated. These include: a) development of long-period seismic instrumentation techniques with emphasis on increasing sensitivity and on discriminating against noise; b) investigation of the general characteristics of seismograms with emphasis on studies of higher mode surface waves, core phases, and multiples of P and S and methods to selectively enhance these phases; c) investigation of aspects of the New Global Tectonics relevant to the problems of detection and identification of seismic events and of selecting optimum sites for seismic instrumentation; d) using large array data, conduct detailed studies of wave propagation, of source characteristics, and of surface and body waves of short and long periods originating at teleseismic distances with particular emphasis on regions with complicated crust and mantle structure such as island arcs and arc-like features; e) conduct studies of near earthquakes and explosives to determine properties of the source, or the propagation path of the crust and upper mantle in the vicinity of explosions and shallow earthquakes; f) development of high-speed computational techniques for the solution of (associated) computational problems that arise in connection with the other items in the Work Statement; g) conduct a comprehensive seismic and geologic study of anomalous and intraplate earthquake events falling within the explosion discrimination, their respective tectonic setting and methods of their positive identification; h) develop earth models of continent-continent collision zones in Europe, Asia and South America, according to recent concepts of plate tectonics. These models will include factors of focal depth, ray tracing, stress drop, and mapping of zones of seismic excitation and generation of deep earthquakes.

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residual						
sea-floor spreading						
seismic body wave						
seismic discrimination						
seismic source parameter						
shear wave						
slip vectors						
stress drop						
strike-slip						
strong-motion						
subduction zone						
surface waves						
synthetic seismogram						
tectonics						
thrust fault						
transform fault						
V_p/V_s						

Line - Item 0001a

The operation of the Lamont-Doherty long-, intermediate-, and short-period seismograph stations at Palisades, New York (PAL), Sterling Forest, New York (SFO), and Ogdensburg, New Jersey (OGD) continued for the duration of this contract.

Line - Item 0001b

1. During the last period, a study of earthquakes with anomalously large high-frequency content was begun. These events are of special interest because they are the most likely ones to be confused with explosion signals. High-frequency earthquakes are also called high stress earthquakes because high stresses in the source region are the most likely cause for relatively strong high frequency content.

Before the discrimination problem for individual high stress events is attacked, we must recognize these events and we may ask whether there are systematic regional variations in the stresses. Higher stresses are expected to be accumulated in regions where new faults are being created in competent rocks. Low stresses may prevail along well developed active faults. The simplest method to recognize high stress events is to classify earthquakes by the ratio of a high frequency to a low frequency amplitude. A more sophisticated method is to obtain the body wave spectrum of an earthquake over approximately two decades of frequency and determine the stress-drop.

2. A paper by Molnar and Wyss in which stress-drops of shallow earthquakes in the Tonga-Kermadec arc were determined from displacement spectra of body waves was submitted to Physics of the Solid Earth. They analyzed 37 events and found that earthquakes with the highest stress-drops occurred outside the main thrusting zone. They concluded that the high stress-drop events (high-frequency risk) reflected deformation within one plate of lithosphere and that these earthquakes may have created new faults. Molnar and Wyss studied 18 earthquakes with depths greater than normal in the same area and found that earthquakes of intermediate depth had higher stress-drops than shallow ones. This observation corroborated the results by Tsujiura (1969) and Wyss (1970) who both found marked increase in high-frequency content for earthquakes with increasing depth.

3. A paper entitled "The use of body-wave spectra in the determination of seismic source parameters" by Hanks and Wyss was submitted to the Bulletin of Seismological Society of America. Teleseismic determination of body-wave (P, S) spectra, interpreted in terms of the Brune (1970) seismic source model, are used to estimate the parameters, seismic moment, and source dimension for three large, shallow, strike-slip earthquakes occurring on nearly vertical fault planes and for which the same parameters can be determined from field data. These earthquakes are the Borrego Mountain, California, earthquake (April 9, 1968); the Mudurnu Valley, Turkey, earthquake (July 22, 1967); and the Dasht-e-Bayaz, Iran, earthquake (August 31, 1968). A minimum estimate for the radiated energy is low by a factor of 3-10 with respect to the estimate obtained from energy - magnitude relations for these three earthquakes. The stress drops of these events are of the order of 10 bars.

The above studies underline the importance of exact depth determinations for more or less shallow earthquakes. The deeper an event the more high frequencies will be radiated and the more difficult will it be to discriminate it from explosions. The second conclusion from the above studies is that in an average sense there are regional differences in the high frequency content. However, high-stress regions produce occasionally low-stress earthquakes and vice versa.

4. A paper entitled "Seismic body waves in the vicinity of Mount Katmai, Alaska, and evidence for the existence of molten chambers" by Tosimatu Matumoto was published in the Bulletin of the Geological Society of America. The study revealed the disappearance of shear waves along certain paths crossing the volcanic range. A close geographical correlation of these paths with active volcanoes strongly suggests that magma or zones of partial melting exist and are responsible for S-wave shadowing. By the use of the high attenuation of high-frequency P waves, an estimate of viscosity in a magma chamber of 10^8 cgs units is made.

5. A detailed mapping of the attenuation properties of the wedges of mantle behind island arcs and above the descending lithospheric slabs is currently under way. In this study pP and P waves from intermediate and deep earthquakes as recorded on the WWSSN seismograms were used. Preliminary results strongly confirm the existence of the high-attenuation zone behind the Tonga-Kermadec arc as found by Barazangi and Isacks (1971). A study of all the Earth's island arcs and island arc-like structures is being carried out.

6. An algorithm has been developed to calculate difference formulae for boundary and interface conditions arising in the solution of the elastic wave equation by finite difference methods. Using the calculated formula for the corner of a quarter space, a Rayleigh wave was propagated around the corner. Agreement with model experiments was within the computational error. A similar experiment was performed for a three-quarter space and agreement was obtained with the few published values. The algorithm can be used for any model whose boundaries and interfaces can be approximated by straight lines such as wedges, imbedded material, surface elevations, etc.

7. The elastic waves radiated by a stress-free surface, which grows within a pre-stressed medium was made. Earthquakes may reasonably be modeled in this way, and, for cases with a elliptic fault plane, the radiated waves can (suprisingly) be calculated by Cagniard-de Hoop theory. A simple method has also been found to obtain the far-field pulse shape from given motions on the fault plane.

8. A study is being conducted to find the initial phase patterns associated with azimuth for nuclear explosions at NTS and nearby natural events. Long-period WWSSN Rayleigh wave data is used to calculate the initial phase patterns. It is hoped that a specific phase relation can be used in discrimination-detection work.

9. Core phases from three Philippine earthquakes have been studied in the distance range from 110 to 130 degrees using long period WWSSN seismograms. Theoretical seismograms were computed for each of these events, assuming

different core models. Corresponding amplitudes in the observed and the theoretical seismograms were compared either by constructing amplitude-distance curves or by forming the amplitude ratio of a core phase and the diffracted P wave at the same distance. Preliminary results of this comparison are the following:

(1) There is no observed GH branch in the distance range from 120 to 130 degrees. On the other hand, models of the core like Bolt's produce observable amplitudes there. Hence, the transition zone from the outer to the inner core cannot be separated from the outer core by a more or less discontinuous change in physical parameters. It is more probable that there is a gradual change. The observed short period GH arrivals could be due to local inhomogeneities.

(2) Traditional values of the P velocity variation $\Delta\alpha$ across the inner core boundary of 0.9 to 1 km/sec necessarily lead to shear velocities β_{ic} at the top of the inner core of 5 to 6 km/sec. Even then, the agreement between observed and theoretical seismograms is not very good.

(3) Reduction of $\Delta\alpha$ to 0.6 km/sec which is compatible with short period amplitude data leads to β_{ic} values between 3 and 4 km/sec, and the agreement between observed and theoretical seismograms is much better. Changes in the density variations $\Delta\rho$ give only minor changes in β_{ic}.

10. Investigation of precursors to the seismic phases PKPPKP has been continued. In order to explain the short-period observations, a reflecting horizon within the upper mantle does seem to be required at a depth of 650 km. A paper entitled "Seismic waves reflected from velocity gradient anomalies within the Earth's upper mantle" has been submitted (February, 1972) to the journal "Zeitschift für Geophysik."

11. Sykes and Sbar have been making an extensive study of intra-plate earthquakes, those shocks that occur within large lithospheric plates. They may be contrasted with the more numerous earthquakes that occur along major plate boundaries defined by island arcs, strike-slip faults and mid-ocean ridges. Intra-plate earthquakes, however, are fairly common, particularly in North America and in Asia. It is these lone types of events within areas that are not normally thought of as highly seismically active that must be identified as earthquakes and not become "false alarms" by misidentification as possible underground nuclear explosions. Many of these events appear to be enriched in the high-frequency part of the spectrum. A preliminary analysis would indicate that they fall near the extremity of the earthquake population on an M_s-m_b population and that they do not fall in the explosion population. We intend to examine these aspects of intra-plate earthquakes more thoroughly. Clearly it is events of this type, and especially anomalous events like the Tibetan earthquakes that fall near the explosion population, that should receive the greatest scrutiny in the discrimination-detection program.

We find that focal mechanisms can be obtained using WWSSN data for intra-plate earthquakes down to about magnitude m_b 5.0 to 5.2. For events of this size a long-period P wave is usually not discernible on the standard WWSSN long-period records and hence, first motion cannot be obtained on a long-period basis. Nevertheless, very reliable first motions can be read from the short-period records. The reason for this appears to be the relatively

small source size for which the short-period instruments see the focal region as essentially a point source. Consequently such events are relatively rich in short-period energy. There are two possible reasons for the increase in short-period energy. These would be a high-stress drop during the earthquake or a high Q through the crust and upper mantle beneath the source. We feel that the latter is probably the most important effect, since the ray paths near the source traverse material through the crust and upper mantle that is not young or heated or involved in recent tectonism like those of earthquakes along many plate boundaries.

Most of these shocks can be identified as earthquakes from the amplitude variation of their radiation pattern, both that of the short-period P waves and of the Rayleigh waves. For stations at teleseismic distances the closer stations are often near one of the two nodal planes, while stations at great distances and even at PKP distances record relatively large P waves. An examination of records from stations in the distance range 30° to 40° would indicate that the P wave might be too small to yield a reliable focal mechanism solution. Nonetheless, for many of the intra-plate earthquakes from which the axis of maximum compression is nearly horizontal, the maximum radiation for P waves is nearly vertically downwards. Hence, very distant stations record very large short-period P waves compared to those of closer distances. This pronounced amplitude effect, of course, is not observed for nuclear explosions, but is related to the focal mechanism of the earthquake.

Focal mechanism solutions have been obtained for about 30 intra-plate earthquakes. By far the most dominant type of solution involves thrust faulting. Most of the world's seismograph stations receive compressions for these events, but a few stations almost always record well-defined dilatations, or other stations can be identified as being near the nodal plane from their P wave signatures. Most of these events are probably quite shallow.

We are undertaking an analysis of the radiation pattern of Rayleigh waves from this series of intra-plate earthquakes. For a few of the larger intra-plate earthquakes other investigators have shown that the radiation pattern for Rayleigh waves has two lobes with the maximum along the P axis. The use of Rayleigh waves will permit an accurate determination of the trend of the P axis, and it should provide additional evidence that these events are, in fact, earthquakes and not explosions. A more detailed analysis of the spectrum of the P wave of intra-plate earthquakes is also underway.

12. Techniques developed for the study of individual events in a swarm-type earthquake sequence in the northern Gulf of California (Tatham and Savino, 1973) are currently being adapted and applied to the examination of events termed "anomalous" in Central Asia. For the swarm-type events, Love and Rayleigh wave observations at a single very long period (VLP) high-gain station (ALQ) were used to discriminate between possible focal mechanisms. The assumed possible solutions resulted from an understanding of the tectonics of the region. Mechanisms for events with body-wave magnitudes well below 4.0 were discriminated by observations of surface waves at the single station situated approximately 8° from the epicentral region. The method of fault plane solution discrimination consists of comparing the relative amplitudes of Love and Rayleigh waves on an optimum azimuth, and relating them to those predicted by calculated radiation patterns for assumed mechanisms.

To extend the success of this technique to Central Asian events, it would be desirable to use records of the WWSSN, as well as the VLP high-gain records. For one of the small Gulf of California events, a dozen seismograms from 4 WWSSN stations were digitized, and the Love and Rayleigh wave radiation patterns compared to the results of the previous study. These observations were entirely consistent with the earlier study, confirming the validity of the transformation to WWSSN data.

At the present time, seismograms from WWSSN stations in Central Asia are being examined to determine which specific events the above described technique can be applied to. To date, some 900 film chips have been visually inspected, and digitization of individual seismograms is currently in progress.

It is felt that the anomalous surface-waves of the "anomalous events" may possibly be related to the focal mechanism as well as to a possible depth effect. This possibility is to be investigated by expanding the data set of published P-wave determined focal mechanisms to smaller events by use of Love and Rayleigh wave observations. The conventional fault-plane solutions will act as tectonic control in discriminating between the possible focal mechanisms of smaller events, including some of the anomalous events.

In addition to the focal mechanism and focal depth considerations resulting from surface wave observations of anomalous events, improved understanding of the nature of intraplate earthquakes (Sykes and Sbar, 1973) has led to the possibility of using short-period surface wave velocity dispersion for resolving crustal structure as shallow as ½ km (Tatham, 1973). The short-period character found in surface waves generated by intraplate earthquakes allows this unusually shallow resolution, thus making a new set of data available for studying the shallow crust.

13. Ongoing research toward the discrimination of anomalous events--those natural earthquakes that plot in, or near, the explosion population on an M_s-m_b diagram--has led to the identification of all such events located near the eastern Himalayas as natural earthquakes. Most of the reported anomalous events (about 25) are located in Tibet in a particular tectonic setting associated with the eastern termination of the Himalayas. At this point several tectonic trends of the Himalayas, an area of continent-continent collision, converge toward an intersection with the northward projection of the Andaman-Burman arc. Thus, the tectonic regime of these anomalous events is not part of the Himalayas but rather appears to be related to "end-effects" at their eastern terminus. Previous investigators have suggested that anomalous events result from strong excitation and efficient propagation of body waves. Our study of the regional tectonics of the area reveals several potential sources of poor surface wave excitation. The crust of the Tibetan Plateau, which from meager data appears to be almost twice as thick as normal continental crust, offers a medium for the occurrence of earthquakes at moderate focal depths. Rayleigh waves of the fundamental mode are poorly excited by earthquakes at such depths. The thick crust also provides a wave guide for the efficient propagation of Love waves and higher-mode Rayleigh waves, and it is found that observations of these waves provide a discriminant for some of the anomalous events. In particular observations of higher modes offer an

especially attractive discriminant. Since the degree of excitation of various modes depends mainly on focal depth, no explosion data are required for comparison of earthquakes and explosions. These higher-mode observations, combined with more reliable m_b determinations, identify all of the reported anomalous events in Tibet--with the exception of a single sequence of events--as natural earthquakes. The remaining sequence of anomalous events, none of which is in the explosion population, occurred in a very limited area (about 50 km or less on a side) where a concentration of tectonic stress may be anticipated. Thus, these few remaining anomalous earthquakes may be related to high tectonic stress, perhaps in association with the formation of a new fault. High-stress earthquakes often have small source dimensions, and hence only weak surface waves are excited. This study places the occurrence of these remaining anomalous events with the complex tectonic setting of the eastern terminus of the Himalayas. Observations of dilatational first motions, however, allow these events to be discriminated. Thus, all of the reported anomalous events in Tibet are identified as natural earthquakes. To our knowledge, all events from Tibet or elsewhere that have been discussed in the literature as being anomalous can, in fact, be identified as earthquakes using one or more of the above mentioned techniques.

14. The excitation of higher modes by shallow events large enough to allow focal mechanism determination is being examined. The spectra of the fundamental mode Love and Rayleigh waves observed at several stations are used to establish the depth of the events. Since all of the events studied are in a limited geographical area, a comparative event technique can be used to remove propagation path effects from the spectra. Once the depths and mechanisms are known, the events can be used as standards for establishing the detailed characteristics of excitation and propagation of the higher modes. In turn, these characteristics can be helpful in classifying other seismic sources, particularly those small events for which higher modes are observed, but which are too small for reliable measurement of the complete spectra of the fundamental mode. For some small, anomalous events in Kazakh, and M_s based on the higher mode amplitudes may be more reliable than an M_s based on the short-period fundamental mode Rayleigh waves.

Line - Item 0001c

1. A paper of focal mechanisms for shallow earthquakes occurring from 1964 to June, 1969, in the region from New Guinea to the New Hebrides titled "Focal mechanisms and plate tectonics of the southwest Pacific" by Johnson and Molnar was submitted to the Journal of Geophysical Research. Ninety-six new focal mechanism were determined for earthquakes on the belt of seismic activity separating the Pacific and Australian plates. The direction of convergence of these plates varies from NE-SW to east-west. The Australian plate underthrusts the Pacific plate to the ENE under the Solomon and New Hebrides Islands, and overthrusts the Pacific to the east along the Tonga-Kermadec arc and North Island of New Zealand. Between the southern part of the New Hebrides arc and the northern end of the Tonga arc, several mechanisms are consistent with a zone of transform faulting between the arcs, but the tectonic boundary in this area is clearly more complex than a simple transform fault. The data for the Macquarie Ridge concur with the idea that the pole of rotation for the Pacific and Australian plates is nearby and to the east of this feature. The data also suggest a NNE-SSW convergence of the Pacific plate and the Australian plate in northwestern New Guinea.

2. A paper entitled "Earthquake fault parameters and tectonics in Africa" by Maasha and Molnar has been submitted to the Journal of Geophysical Research. Fault plane solutions of earthquakes in southern Africa indicate that the least compressive stress is oriented approximately east-west nearly parallel to that in the northern part of the rift system. Seismic moments, source dimensions, and stress drops were determined for eight earthquakes from body and surface wave spectra using the theory of Brune (1970). Spectral estimates of these quantities for the 1966 earthquake in the Republic of Zaire agree well with those observed in the field. Relatively higher stress drops are found for events not associated with rift faulting. If higher stress drops indicate higher rock strength, then these, with other geological and geophysical data, suggest that the northern part of the rift system is similar to ocean ridges and behaves as a plate boundary, but the southern part is different and is not a plate boundary. The tectonics associated with the northern part of the rift system appear to migrate southwards.

3. Sykes has examined the location and possible depths of several earthquakes in Tibet for which M_s-m_b values are close to those of explosions. He finds that these earthquakes are located on or very close to the Indus suture zone, the position at which the Indian plate is thought to have collided with northern Eurasia. These earthquakes are located at the eastern end of the Himalayan arc where it terminates against structures with a northerly strike in Burma. A similar zone of earthquakes is found at the western end of the Himalayan arc where it meets north striking features in Pakistan. The latter intersection occurs in the Hindu Kush where abundant intermediate focus activity is found. A well-defined dipping seismic zone is present beneath the Hindu Kush for depths from about 150 to 250 km. Russian workers have found that intermeidate depth earthquakes in the Hindu Kush suffer very little attenuation when they travel to their instruments in the Garm region just to the north of the Hindu Kush. Seismic rays travelling upwards through the diffuse zone of earthquakes above the Hindu Kush source suffer greater attenuation. The well-defined zone of intermediate depth earthquakes in the Hindu Kush is thought to represent the last remnant of ocean crust that was consumed when India collided with Eurasia. The Tibetan zone at the other end of the Himalayan arc may also be the site of sub-crustal earthquakes or a region of high stress related to hinge faulting at the end of the arc. Thus, the best explanation for the M_s-m_b anomaly for the Tibetan earthquakes is that these shocks are somewhat deep (i.e., about 50 km) or that they are a high stress drop associated with the thrusting of two continental plates or associated with hinge faulting at the end of the arc.

Plate tectonics has so far been very successful in explaining many features of island arcs, mid-ocean ridges, and transform faults. To date, it has been less successful in explaining continental collision which is apparently occurring in the broad zone north of the Himalayas and across central Asia. A great deal of geological information, however, can be brought to bear upon the problem of plate tectonic interactions in this area. It is perhaps not suprising that either high stress drop earthquakes or earthquakes with a depth of 50 to 70 km may occur in this region and may present problems for discrimination of an M_s-m_b basis. The Tibetan events are some of the largest known earthquakes for which the M_s-m_b values are similar to those of underground explosions.

4. P-travel times of the CANNIKIN nuclear explosion were studied using NOAA and Lamont seismic data along the Aleutian island arc and in Alaska. Eastward from the shotpoint J-B residuals increase about -2 sec to -6 sec along the arc from Adak to Kodiak. A north-south change in residuals has observed with small negative residuals (-2 sec) in central Alaska and high negative residuals (-6 sec) near the Gulf of Alaska. CANNIKIN P-resiudals were 1 to 2 seconds more negative than those of the LONGSHOT nuclear explosion. The interpretation of the observed residual pattern indicates a continental velocity structure in the wedge above the high velocity slab and beneath the ridge that is located between the trench and the active volcanoes. This velocity structure was previously obtained from teleseismic P-wave and surface wave data, and is similar to a structure usually encountered beneath an orogenic belt. The effect of various station distributions on the relocation of CANNIKIN was investigated, to find a better means of relocating Aleutian earthquakes.

5. Travel times and frequency content of seismic P waves from nuclear explosions and of P and S waves from Aleutian earthquakes have been analyzed to derive seismic velocities and attenuating properties of the crust and upper mantle beneath and adjacent to the Aleutian island arc. The body wave data are supplemented by Rayleigh wave dispersion data for paths along the arc towards a station on Amchitka Island. Three main tectonic features can be distinguished: 1) The high-Q high velocity slab of the underthrust Pacific plate. 2) A thickening of the oceanic crust in the overthrust Bering Sea plate beneath the island arc ridge between the trench and volcanic line with a velocity structure almost identical to that for a continental margin. 3) A zone of moderately anomalous low velocities and Q in the mantle beneath the Bering Sea Abyssal Plain for ray paths between the arc and a station on St. Paul Island. This zone appears to be just north of the volcanic line. Its depth and lateral extension, however, are not well defined from the presently available data. The low-Q, low velocity zone beneath the Bering Sea is not as well developed as beneath presently active zones of ocean floor extension in some interarc basins, e.g. the Lau basin behind the Tonga arc.

6. A recently developed method of three-dimensional seismic ray tracing is employed to reinterpret P-wave travel-time residuals of the Longshot nuclear explosion on Amchitka, Aleutian Islands, in terms of plate tectonic structure near the source and near the teleseismic stations. The observed pattern of P residuals from Longshot can be explained by an 80 km thick, descending lithospheric plate that reaches a depth of 250 km beneath the Aleutian arc, and has 7% to 10% higher P-wave velocities than the surrounding mantle. The anomalous high velocity at 100 to 200 km depth indicates that the descending plate at that depth is colder than the surrounding normal mantle by several hundred degrees.

The P travel-time anomaly associated with the dipping plate is eliminated from the total P residuals to obtain new worldwide station residuals. The station residuals are then grouped according the a proposed tectonic code that distinguishes between active zones of plate convergence, divergence, and transcurrent shear as well as between volcanically active regions and stable oceanic and continental regions. The tectonically grouped station residuals show a strong correlation with various tectonic features. On the average P arrivals in continental shields are earlier by 1 second

than in younger (but stable) continental and oceanic provinces, and earlier by 2 seconds than in active volcanic regions. The station residuals indicate that lateral velocity anomalies within the upper 200 to 250 km of the earth's mantle are commonly associated with tectonic features that lateral velocity contrasts may in some cases exceed 10% of the average velocity. A new P-residual map for the United States and adjacent Canada is presented.

7. The group velocities of Rayleigh waves in the period range from 20 to 60 seconds were analyzed from records of a seismic station operated on Amchitka Island using seismic events in the South Pacific, Japan, the Kuril-Kamchatka region, and from along the Aleutian Arc. The original mixed-path group velocity data were separated into pure oceanic-path and pure ridge-path group velocities. Throughout the entire period range group velocities for the Aleutian ridge were found to be consistently by at least .3 km/sec slower than for the oceanic regions in the Pacific. Systematic inversion of the group velocity data indicates that the S velocity in the upper 120 kilometers of the mantle beneath the ridge and above and adjacent to the inclined seismic zone are lower by nearly 10% than in a normal oceanic mantle and that the crust beneath the ridge is almost 30 kilometers thick, typical for and similar to the crust and upper mantle structure of a young continental orogenic belt.

8. Focal mechanisms are presented for earthquakes located along the Near Islands and Commander Islands for the western Aleutian Archipelago and along the northeast coast of the Kamchatka peninsula. Along the southern slope of the Aleutian ridge mechanisms indicate shallow angle thrusting with a slip vector parallel to the trend of the ridge striking N50°W. Along the northern slope of the Aleutian ridge, the area between the Near Islands and the western slope of the Shirshov ridge is currently aseismic, but west of the Shirshov ridge a zone of right lateral strike slip mechanisms occur along a well defined bathymetric escarpment. Strike slip motion along the trend of these zones occurs as far west as 165°E midway between the contours defining the end of the Aleutian ridge and the beginning of the Kamchatka peninsula. Mechanisms along the Kamchatka peninsula near the Aleutian ridge junction define three tectonic zones. North of the junction, between 58°N and 56°N, mechanisms at moderate angle thrusting with a component of strike slip motion with a slip vector the same as that along the Aleutian ridge. At the junction, between 56°N and 54°N there is no longer a component of strike slip motion. South of 54°N thrusting occurs at shallow angles perpendicular to the coast of Kamchatka.

9. Historical seismicity studies of the eastern section of Canada and northeastern United States indicate the existence of a seismic belt trending in a northwesterly direction and passing through Boston and Ottawa. This zone coincides with the White Mountain magmas, the Monterregian hills and the Ottawa-Bonnachere graben. Portable seismographs were used to supplement the permanent stations of the Lamont-Doherty seismic net for the recording of the first arrival from the Cannikin nuclear explosion. The stations were set up across the above seismic belt and adjacent areas. Arrivals from these stations show early arrivals with respect to a Jeffreys-Bullen earth, residuals ranging from 4.2 to 6.8 sec. All stations inside the seismic belt

show larger (6.0 to 6.8 sec) residuals than stations outside the belt (4.2 to 5.8 sec). These residuals were compared with residuals calculated from a model that utilizes a dipping slab under the Aleutian chain. The effect of this model does not significantly alter the above residuals. The relative difference in residuals on either side of the seismic belt can be explained by differences in the crust and upper mantle under this area, possible a result of magmatic activity during the Jurassic and Cretaceous. The seismic anomalies suggest that a weak zone may exist in the North American plate. This weakness may allow stress in the plate to be relieved in the form of earthquakes localized around the zone of weakness.

10. A large region of high horizontal compressive stress is delimited in eastern North America from a combination of fault plane solutions of earthquakes, <u>in situ</u> stress measurements, and geologic observations. Each of these methods, including <u>in situ</u> stress determination by both overcoring and hydrofracturing, yield nearly identical directions for the principal stresses. The maximum compressive stress trends east to northeast over an area extending from west of the Applachian Mountain system to the middle of the continent, and from southern Illinois to southern Ontario. In this region earthquakes appear to occur in regions of high stresses along weak zones in the lithosphere. An example of such a weakness is the seismic belt trending from Boston to the northwest through Ottawa. This seismic zone appears to be located along a continental extension of the Kelvin seamount chain which is postulated by others to be a fracture zone related to the early opening of the North Atlantic. Similarly the 1929 Grand Banks earthquake and the Charleston, S.C. seismic trend appear to be along extensions of other oceanic fracture zones.

The relationship between high stress and weak zones may provide a means to assess the earthquake risk within plates. The observed pattern of stresses appears to be Mesozoic or later in origin, and does not seem to be significantly influenced by glacial rebound. This work supports Voight's hypothesis that the compressive stress observed within the North American plate may be generated by the same mechanism that drives the movements of large lithospheric plates. If this is indeed the case, stress measurements may furnish one of the best clues to the driving mechanism of plate tectonics.

11. A study of geotectonics of Africa is done in this study using spectral analysis of seismic signals of eight earthquakes. It is found that earthquakes on the East African rift system have lower stress drop to seismic moment ratios than those occurring off the rift system.

12. The existence of a zone of extremely low compressional wave velocities in the uppermost mantle beneath most of the Lau basin, an inter-arc basin located west or behind the Tonga island arc, is studied. This study augments the understanding of the new global tectonics that are of particular relevance to the problems of detection and identification of seismic events. Velocities beneath the basin appear to be as low as 7.1 km/sec. In contrast, times of P and S waves traveling beneath and parallel to the Tonga-Kermadec ridge indicate velocities of 8.45 and 4.75 km/sec, respectively. Although the lateral boundaries of the zone of low velocity beneath the Lau basin are not well defined, they coincide approximately with the boundaries of the zone of high seismic wave attenuation that exists beneath the Lau basin.

The large difference (up to 15%) between P wave velocities beneath the Lau basin and areas adjacent to it probably requires partial melting in the upper mantle beneath the Lau basin. P and S velocities measured parallel and approximately perpendicular to the Tonga trench do not differ significantly and hence provide no evidence for anistropy in the Pacific lithosphere.

13. A study for several possible criteria for forecasting the locations of large shallow earthquakes of the near future along major plate boundaries, and for assigning a crudely determined rating to those forecasts has been conducted. This study will provide useful information about optimum siting of seismic stations and networks in reference to potential earthquake risk.

These criteria are based on the past space-time pattern of large earthquakes, the lateral extent of their rupture zones, and the direction of rupture propagation. The criteria are applied in two stages. Application of the first set of these criteria to major plate boundaries along the eastern, northern, and northwestern margins of the Pacific from Chile to Japan and also to the Caribbean loop east of about 74°W results in delineation of several areas of special seismic potential along each of the boundaries. The phrase "special seismic potential" is used in this study only to indicate those segments of plate margins that fulfill certain specific criteria. However, if the criteria are valid, at least some, and perhaps most, large shallow earthquakes of the near future within the zones examined will occur near these locations. At present, the validity of the criteria is not firmly established and profound social changes based on these predictions are uncalled for, but the forecast presented here can, at the very least, serve as a guide in selecting areas for intensive study and instrumentation prior to the occurrence of a major earthquake. In certain areas where additional information is available, the subsequent application of a second set of supplementary criteria focuses speical attention on certain of the areas delimited by the first set of criteria.

14. Large, shallow earthquakes ($M > 6.9$) that have occurred since 1968 have been relocated to determine whenever possible the extent of rupture along the northern and western boundary of the Phillipine Sea plate. Two areas along the seismic zone east of Mindinao have not experienced a large, shallow, earthquake in at least 30 years and are areas of special seismic potential. A compilation of historic, microscopic, and relocated instrumental data shows that the Phillipine fault which runs about 1200 km from Luzone to Mindinao probably has ruptured over at least half its length during the last 105 years. Consequently, the activity at the Phillipine fault indicated that plate motion in this region may be partially or totally accommodated by this fault.

The Ryukyu Island arc, between 123° and 130°N, has not experienced a large shallow earthquake in 50 years and is relatively aseismic for a plate boundary. A study of historic Japanese sources indicates, however, that large, destructive earthquakes with associated tsunamis have occurred along this portion of the plate boundary is an area of special seismic potential.

15. The first stage of a tectonic study of the Scotia Sea region is nearing completion. The focal mechanisms of many earthquakes occurring in this region from 1963 through 1972 have been determined using the first motion of P-waves and the polarization of S-waves as recorded on the

long-period seismographs of the WWSSN stations. However, from body wave observations alone it is often difficult to describe accurately the nature of faulting in an area far from any seismic stations such as the Scotia Sea. The limited azimuthal and radial distributions of body wave observations can eliminate some possible mechanisms, but leave many other possibilities open. For example, from the body wave study, it is known that normal faulting cannot be the mechanism of the largest earthquake in the Drake Passage. It had been suggested that the submarine ridge in this passage between South America and Antarctica is a site of sea-floor spreading, where either normal or strike-slip faulting would be expected. Normal faulting has been eliminated as a possible mechanism, but either strike-slip or thrust faulting is consistent with the limited body wave data. However, if observations of the azimuthal variation of Rayleigh wave amplitudes are included, it will be possible to reliably determine the mechanism of the event. If the earthquake is characterized by thrust-faulting, it will be strong evidence that the submarine ridge is a compressive feature rather than the locus of sea-floor spreading as previously postulated. This earthquake, and several other events crucial to the tectonic interpretation of the area have been singled out for further detailed study using surface waves. Digitization of the long-period records of the WWSSN stations is in progress.

In addition, the surface waves from two earthquakes in this area which appear to be multiple shocks will be studied. From the body waves, it appears that in these two cases the first event is followed within 30 seconds by another event with the same mechanism. One of these shallow events, near the Africa-South American-Antarctica triple junction, appears to have unusually large amplitude long-period Rayleigh waves (greater than 60 sec) compared to the short period amplitudes (15 to 20 sec). The P-waves from this event observed in South America appear to have a very long-period precursor followed by a sharp impulsive signal. This may indicate relatively slow sliding on the fault preceding the sharp onset of rupturing. The object of this study will be to investigate the possibility that multiple shocks seriously hamper the interpretation of the surface wave radiation patterns and the determination of the focal mechanism. It may also be possible to increase our understanding of the rupture process in these apparently complex events.

16. The importance of changes in focal mechanism with depth within the New Zealand crust has been discussed in earlier reports. In brief, earthquakes in the upper crust reflect regional compression in a WNW-ESE direction; they reveal strike-slip and thrust mechanisms that can be related to the regional geology. In contrast, underlying earthquakes 20-35 km deep indicate a markedly different stress distribution with normal faulting predominating. This conflict with the regional tectonic stress field (at relatively shallow levels) offers a clue to explaining similarly anomalous focal mechanisms behind other island arcs. Shallow normal-faulting mechanisms that conflict with the inferred stress pattern have been found behind the Central American arc, the Aleutian arc, the Indonesian and Phillippine arcs, and the Himalayan and Burmese arcs.

To explain the change in mechanism with depth in New Zealand, efforts have been focused on a critical problem. Do the earthquakes 20-35 km deep in fact occur within continental crust, or could they occur within subducted oceanic lithosphere? Beneath central New Zealand the oceanic plate consumed

at the Hikurangi trench could have a very small dip and be coupled to the continental crust. Limitations of the New Zealand seismograph network prevent a resolution of the upper Benioff zone behind the Hikurangi trench. The Benioff zone is generally assumed to lie well beneath a continental crust 30-35 km thick.

A recent documentation of anomalous normal faulting in south central Alaska suggests a similarity to New Zealand. In the eastern Aleutian arc, the 50 km isobath of the Benioff zone lies beneath the western Kanai Peninsula, more than 350 km from the Aleutian trench; in other words, the oceanic plate remains coupled to the continental crust for a large distance before turning down into the mantle. The normal faulting occurs near the region of down-turning (well behind the trench, where such normal faulting is oridnarily observed). If a similar configuration occurs beneath New Zealand, the anomalous earthquakes 20-35 km deep may manifest intraplate deformation within the oceanic plate rather than depth-varying stresses within the continental crust.

Gravitational constraints upon alternative crustal models for the New Zealand region are being analyzed. Also, microearthquake data are being studied for suggestions of different stress levels or source properties below and above 20 km. Gravitationally, there appears to be allowance for raising the upper part of the oceanic plate, say as high as 20 km, to include the earthquake activity in the problematical 20-35 km depth range. Significantly, such a coupling with the continental crust (with a small dip away from the trench) may explain aspects of the regional gravity field in this area. To the north, a characteristic free-air gravity anomaly is associated with the Kermadec arc: a large negative anomaly coincides with the trench, a positive anomaly rises over the seaward wall of the trench, and another positive anomaly rises behind the trench. This triplet appears in New Zealand, but the negative anomaly is displaced 250 km landward from the trench -- as apparently is the axis of downturning of the oceanic plate. An understanding of the gravity field in New Zealand in this context promises to contribute to explaining the common gravity triplet elsewhere -- also to defining areas where (in the absence of dense seismic networks) the upper levels of a Benioff zone may be poorly defined but where the oceanic plate may be shallower than assumed.

17. The relation of earthquake focal mechanism to global tectonic patterns has been a constant theme in our work for many years. The tectonic pattern of the plate junctions in the South Atlantic Ocean has never been clear, however. Earthquake focal mechanisms have succeeded in defining the nature of the plate boundaries in this region.

Focal mechanism solutions for 46 earthquakes that occurred in the South Atlantic Ocean, in the Scotia Sea, and in southern Chile during the period 1963-1973 have been examined. The slip vectors of shallow earthquakes indicate that the South American plate is moving directly west with respect to the Antarctic plate at the ridge-fault-fault triple junction in the South Atlantic. The directions of motion of Africa with respect to the South American and Antarctic plates at the triple junction are N70°E and N47°E, respectively. The SA-ANT relative motion between the triple junction and the South Sandwich trench is best described by a pole of rotation at 80°S, 166°W, with angular rotation rate of 0.24 deg/my.

Shallow earthquakes along the South Sandwich trench indicate the oceanic portion of the South American plate is being thrust under the South Sandwich arc in an E-W direction. Most of the earthquakes at the northern end of the arc are due to hinge-faulting or bending stresses within the underthrust oceanic plate. The focal mechanisms of intermediate depth events beneath the arc indicate downdip extension in the northern end of the downgoing slab and downdip compression in the southern end. This change in the stress pattern may be caused by reduced negative buoyancy forces in the younger, southern half of the subducted plate. The seismicity and mechanism solutions suggest that the SA-ANT relative motion in the Scotia Sea region is taken up on both the North and South Scotia ridges. However, the plate boundaries in this area and in southern Chile are not well-defined. There does appear to be a consistent pattern of horizontal compressive stress directed ENE-WSW throughout the Scotia Sea region, probably induced by the convergence of the South American and Antarctic plates.

The SA-ANT relative motion observed in this study is not consistent with the motion predicted from the summation of motions observed on other plate boundaries. This discrepancy may be due to (1) systematic errors in the data, (2) a recent change in plate motions, or (3) minor, non-rigid plate behavior. The third explanation is preferred, because internal deformation of the plates at very slow strain rates can explain other examples of seemingly inconsistent plate motions, and may also account for the existence of diffuse, intraplate seismicity. The apparent relative drift of hot spots may also be due to internal deformation of the plates after the seamount chains are created. This work has been submitted to the Journal of Geophysical Research.

18. In considering anomalous and intraplate earthquake events, it was found that observation of higher-mode Rayleigh waves and long-period Love waves may provide useful discriminants. The details of these observations are discussed in Item 1g. The observations, however, have special significance in the optimum siting of seismograph stations. Since higher mode propagation requires some kind of crustal wave-guide, station siting should be on a crustal structure similar to that of the source, with a consistent propagation path between the two. Hence, optimum siting requires installation of stations on the same continental block as the events to be observed. For Tibetan events, the ideal station location would be on the Tibetan Plateau, offering the surface-wave travel paths entirely across the observed double-thickness of continental crust.

The siting of stations for the observation of long-period Love waves is somewhat less restrictive than for the observation of higher-mode Rayleigh waves. Significantly, long-period Love waves, but not long-period Rayleigh waves, were observed for some anomalous events by the very long period (VLP) high-gain seismograph at CHG. This observation suggests that Love waves can be used as a discriminant, and that the long-period minimum in the noise spectrum may be exploited to reduce the surface-wave detection threshold for anomalous events.

Line - Item 0001d

1. A paper entitled "Mantle wave analysis by a phase-equilization-and-sum-method for the Montana LASA long-period data" by Kazuo Hamada was published

in the Bulletin of the Seismological Society of America. A paper entitled "Mantle Rayleigh waves for shield, oceanic, and tectonic areas using LASA long-period data" by Kazuo Hamada was submitted to the Journal of Geophysical Research.

By using LASA long-period digital data and high-gain digital data at Ogdensburg, New Jersey, group velocities of mantle Love and Rayleigh waves were determined by means of a recently developed new method. Combining these group velocities with Kanamori's phase velocity data, regionalized shear-velocity models of the upper mantle were inferred. Important conclusions are: a. Shear velocity differences among the different tectonic regions exist at depth less than 300 km. b. Shear velocities in the upper mantle are obviously higher for the shield areas and lower for the tectonic areas than those for the oceanic areas; the velocity difference between the shield and tectonic models is approximately 10% at depths less than 100 km, decreasing gradually; 5% at a depth of 200 km. c. The shield data do not require a strong low velocity channel in the upper mantle like the oceanic model. d. The tectonic data do not necessarily require the presence of high velocity lid just beneath M-discontinuity. e. The oceanic data require obviously a strong low velocity channel in contrast with the other two models. f. The dispersion of Love and Rayleigh waves for the tectonic regions can be explained well by the different shear velocity structures rather than by the same one; the shear velocities expected from Love waves are higher than those expected from Rayleigh waves by 0.2 km/sec. The velocity differences are concentrated at depths from 150 to 300 km. This discrepancy requires anisotropy or an equivalent laminar-melting structure.

2. A paper entitled "Mantle-wave Analysis by a Phase-Equilization-and-Sum Method for the Montana LASA Long-Period Data" by Kazuo Hamada was published in the Bulletin of the Seismological Society of America. In this paper, a "phase-equalization-and-sum" method was applied to long-period data from vertical-component instruments of the LASA array to obtin dispersion data for mantle Rayleigh waves. With this method, group velocities in the period ranges 50 to 300 sec and 50 to 160 sec were determined for mantle waves from moderate-sized earthquakes ($M \approx 6$) in Mongolia and near Taiwan, respectively, by using recordings which are individually dominated by background noise. Advantages of this method are: (1) Signal-to-noise amplitude ratio is increased by 8 db for periods of 50 to 100 sec, 10 db in the 100 to 200 sec period range, and 5 db at 500 sec period; (2) fidelity is thought to be high because long-period surface waves show almost perfect correlation between sensors after phase equilization; and (3) deviations due to each station are expected to be reduced by $1/\sqrt{N}$ times, where N is the number of stations used. In addition to the usefulness of the phase-equilization-and-sum method, the reliability of LASA long-period digital data is demonstrated.

3. A foreshock-mainshock-aftershock sequence which occurred in June, 1971 in the Kirgiz-Kinkiarg border region is being studied to determine what factors other than source and depth and focal mechanism control the surface wave magnitude

of small events. The National Earthquake Information Center (NEIC) assigned a body wave magnitude of 5.6 to both the foreshock and mainshock, but the surface waves generated by the mainshock were approximately 5 times longer than the foreshock. ISC assigned m_b values 5.4 and 5.3 to the foreshock and main shock, respectively. The surface wave magnitude could be affected by differences in depth, mechanism, stress drop or finiteness, but all possible path and instrument phenomena are eliminated by choosing a sequence which is limited in duration and location. The mechanism and depth of the events can be deduced from comparison of the azimuthal variations in the frequency-dependent radiation patterns of the amplitude and initial phase of the Rayleigh and Love waves.

Evernden (1975) suggested that the primary factors controlling M_s of small events (less than about m_b 5.5) are depth and focal mechanism and that stress drop and source length are unimportant. However, differences in mechanism and depth do not appear to adequately explain the dramatic variation in surface wave amplitude within the series of aftershocks. For example, one aftershock, with m_b 5.2, generated surface waves roughly 12 times larger than another aftershock with m_b 5.1. The contrast cannot be attributed to an unusual combination of depth and mechanism effects on the surface wave amplitudes, because the long-period body waves are affected to a similar degree. The earthquakes in the sequence can be divided into two categories; those which excite long-period signals efficiently, such as the main shock and several aftershocks; and those which do not, such as the foreshock and the majority of aftershocks. The primary difference between the two groups may be in the finite size of the source. As observed teleseismically the second group typically generates a very simple, short-period P-wave with most of the energy concentrated within the first 1 to 2 sec., suggesting nearly a point source. However, earthquakes within the first group generate a much more complex P-wave, with substantial energy spread out over the first 10 to 15 sec. These observations suggest that finiteness of the source can play an important role in controlling M_s:m_b even for earthquakes with body wave magnitude 5.2 or smaller.

Line - Item 0001e

1. A paper entitled "Microseismicity and tectonics of the Nevada seismic zone" by Frank J. Gumper and Christopher Scholz was submitted to the Bulletin of the Seismological Society of America. Microseismicity, composite focal-mechanism solutions, and previously published focal parameter data are used to determine the current tectonic activity of the prominent zone of seismicity in western Nevada and eastern California, termed the Nevada Seismic Zone. The microseismicity substantially agrees with the historic seismicity and delineates a narrow, major zone of activity that extends from Owens Valley, California, north past Dixie Valley, Nevada. Focal parameters indicate that a regional pattern of NW-SE tension exists for the western Basin and Range and is now producing crustal extension within the Nevada Seismic Zone. An eastward shift of the seismic zone along the Excelsior Mountains and left-lateral strike-slip faulting determined from a composite focal mechanism indicate transform type faulting between Mono Lake and Pilot Mountain. Based on these results and other data, it is suggested that the Nevada Seismic Zone is caused by the interaction of a westward flow of mantle material beneath the Basin and Range Province with the boundary of the Sierra Nevada batholith.

2. A paper entitled "P-wave spectra from underground nuclear explosions" by Peter Molnar was submitted to the Geophysical Journal of Royal Astronomical Society, London. This paper reports observations of P-wave spectra from underground nuclear explosions for periods greater than about 1 s. The spectra have a maximum at about 2-3 s and decrease rapidly at longer periods. Two phenomena could cause such a decrease: (1) The surface reflection (pP), with its polarity opposite to that of the direct P wave, might differentiate the long-period signal and cause a modulation of $2|\sin\omega t_0/2|$ where t_0 is the interval of time between P and pP; or (2) the source time function for the pressure on the boundary of the elastic zone surrounding the explosion might more nearly resemble an impulse than a step function as often assumed. The data are consistent with the simultaneous occurrence of both phenomena, but they are of insufficient quality or quantity to establish which is more important. If other information shows that the reflection does not have a large effect on the observed spectrum, then the data show that the source time function is primarily an impulse.

In addition, the pronounced difference in spectral content of P waves from earthquakes and underground nuclear explosions suggests a method for identification that is applicable for explosions large enough to be recorded by long-period seismographs at teleseismic distances. This method may be particularly important when long-period instruments are disturbed by other events and methods of identification that rely on analysis of surface waves become inapplicable.

3. A paper entitled "Excitation of seismic surface waves with periods of 15 to 70 seconds for earthquakes and underground explosions" by J. Savino, L.R. Sykes, R.C. Liebermann, and P. Molnar was published in the Journal of Geophysical Research. Using data from high-gain seismographs operating in the deep (543-meter) mine observatory at Ogdensburg, New Jersey, we analyzed the excitation of long-period surface waves by earthquakes and underground explosions for four different regions of the world: western United States, the Aleutians, Novaya Zemlya, and central Asia. The most important result of this study is that discrimination between earthquakes and underground explosions on an M_s-m_b basis is enhanced when the amplitudes of Rayleigh waves with periods near 40 sec, rather than 20 sec, are used to determine M_s. A discriminant based on surface waves with periods near 40 sec is particularly advantageous because of a very stable and pronounced minimum in earth noise in this period range. Love waves also yield a distinct separation between earthquakes and explosions on the basis of M_s (Love) at 20 and 40 sec with m_b, and can be used for discrimination of small events for which no Rayleigh waves are recorded. The discrimination threshold at Ogdensburg is $m_b' \simeq 3.8$ for the western United States at a distance of about 30° and $m_b \simeq 4.4$ for the Aleutians at 70°. All the events studied could be discriminated by using 40-sec Rayleigh waves. Amplitude spectra of Rayleigh waves in the period range 15 to 70 sec were computed for events in the western United States, the Novaya Zamlya region, and the Aleutians. The spectral amplitudes decrease more rapidly with increasing period for explosions than for earthquakes in the western United States and Novaya Zemlya. These spectral differences are consistent with an impulsive source time function for explosions. In the Aleutians, however, the shape of the spectrum of long-period waves for the underground explosion Milrow is similar to spectral shapes for some, but not most, nearby earthquakes Two plausible explanations for this spectral similarity

are contamination of the Milrow spectrum by earthquake-generated Rayleigh waves, or the effects of focal depth and radiation pattern on the earthquake spectra.

4. A study of a temporal change of the travel time observed from the underground nuclear explosions has been continued to utilize the accurately established location and origin time of these events. The travel times measured at a station for the repeated explosions from the Nevada Test Site show a fluctuation of as great as over 1 second. This fluctuation of the travel time primarily resulted from an emergent onset of the wave and from unproper identification of phases. By eliminating some of the events with smaller yield, the fluctuation is greatly reduced. Difference of the distance, depth, and subsoil condition near the station also contribute to the fluctuation of the travel time. Some of the high quality stations (with low ground noise and with accurate time marks) show consistent travel time, and their temporal changes can be examined. At the stations MHC (Mt. Hamilton, California) and KNUT (Kanab, Utah), it is observed that the travel time decreases as the seismic activity near the station increases and the travel time increases rather abruptly when the seismic activity halted. At most of the stations, however, the relation between the localized seismic activity and travel time is rather complicated. This complication implies that the physical condition at intermediate depths that has not been reflected to the seismic activity at shallower depths may play an important role on the temporal change of the travel time.

5. An earthquake swarm was observed in the Blue Mountain Lake area of the southern Adirondacks from early May 1971 until late February, 1972. This swarm provided an unusual opportunity for a detailed field study of earthquakes and a determination of principal stress direction for a region within a lithospheric plate. Thousands of events were recorded, the largest of which had a local magnitude of 4.0, and was felt as far as 80 km from the epicenter. A number of earthquakes were heard as well as felt - the smaller were heard, but not felt.

Thrusting mechanisms were determined from two composite fault plane solutions. The solution for earthquakes above 2 km depth indicates faulting on a plane striking N12°W and dipping 25°E. The fault plane for the deeper events (between 2 and 3.5 km) strikes N31°E and dips 59°E.

The earthquake foci define a surface that dips gently to the east to a depth of 2 km and then steepens, in agreement with the composite fault plane solutions. There is an indication that the shallower earthquakes may not represent renewed motion on a pre-existing fault, but may mark the generation of a new fault by a regional east-west compressive stress. The deeper events may represent the extension of the shallow fault and its deflection to an existing weakness. The axis of maximum compressional principal stress for the shallow composite fault plane solution trends approximately east-west and is nearly horizontal. Geological and geophysical evidence is presented to support the hypothesis that the principal stress in a zone extending from northern New York State to southern Illinois is compressive, large, and horizontal, and trends nearly east-west.

6. Blue Mountain Lake earthquake swarm data is also analyzed to see if an anomalous change in P- and S-wave velocity occurs. Preliminary analysis

revealed that an anomalous change in V_p/V_s occurs before comparatively larger earthquakes in the swarm. A remarkable change in V_p/V_s has been found before an earthquake of magnitude as small as 2.5. As detection and identification of explosions and shallow earthquakes were said to have been difficult in such a small magnitude range, the development of this study may provide a new clue to this problem.

7. The radiation for a three-dimensional problem of brittle fracture is investigated. A crack is presumed to nucleate at a point in an infinite pre-stressed elastic medium, and the crack subsequently grows steadily with subsonic rupture velocities, maintaining the shape of an ellipse. Shear stresses are relieved by the crack, and exact solutions are derived for the acceleration and stress-rate (at every point of the medium) in terms of single integrals and algebraic expressions. The solutions are evaluated analytically at wavefronts and singularities, and numerically, at different points in the medium, for different growth rates of the crack.

8. A perturbation model for triggering earthquakes is described. It introduces a perturbation function which is stationary in time and has a power spectral density. By fitting the model probability density function to a histogram of actual earthquake occurrence, information about the width of the power spectral density of perturbations can be derived. From this information, inferences about the physical nature of different perturbation functions can be made.

The tides are considered as possible admissible perturbations. It is shown that, on the basis of the earthquake data and the model considered, tides may be accepted as possible triggering mechanism for earthquakes in Southern California.

9. The earthquake swarm near Blue Mountain Lake in the southern Adirondacks has proved to be an outstanding source of detailed seismicity data. As reported earlier, the seismic activity accurately defines two fault planes reflecting large horizontal compressive stress, trending nearly east-west.

In addition, careful study of the seismograms from this region has revealed the existence of premonitory velocity changes prior to singularly large earthquakes. The premonitory changes (up to 13%) in the velocity ratio of P and S waves (V_p/V_s) reported earlier for two BML events (M = 2.5 and 3.3) are confirmed by similar changes (up to 10%) prior to another BML earthquake (M = 3.1). To better understand these anomalous changes in V_p/V_s and the focal processes prior to the mainshock, the pre-earthquake period is divided into three periods: A) normal V_p/V_s; B) decrease in V_p/V_s; and C) subsequent increase in V_p/V_s. A general gradual increase in microearthquake activity observed during C is in agreement with the 'dilatancy-fluid flow' model which explains the anomalies in V_p/V_s. A minimum in activity over a broad interval between B and C may represent dilatancy hardening. Composite fault plane solutions and spatial distribution of hypocenters show time dependence and appear to be related. Variations in composite fault plane solutions are similar to those reported by Nersesov and Simbireva for the Garm region. We infer that stress is not uniform throughout the focal region, and suggest that time variant stress may provide another means of predicting earthquakes.

10. Earthquakes that originate from high stress regions are the ones most likely to have relatively strong high frequency content, and these events are of special interest because they are the most likely ones to be confused with explosion signals.

As reported earlier northeastern North America is a region of high compressive stress. The maximum compressive stress trends east to northeast over an area extending from west of the Appalation Mountain system to the middle of the continent, and from southern Illinois to southern Ontario. In this region, earthquakes appear to occur in regions of high stresses along weak zones in the lithosphere. An example of such a weakness is the seismic belt trending from Boston to the northwest through Ottawa.

In conjunction with detailed seismicity studies in apparent weak zones within the region of high stress and in situ stress determinations by hydrofracturing we have observed seismic activity associated with hydraulic mining in western New York State. For the past 2.5 years we have monitored the seismicity of western New York State and in particular the "hot spot" of natural activity near Attica and Dale. In 1971 we noticed a sharp increase in seismicity after high pressures were attained at a hydraulic mining operation in Dale. This fact, the closeness of the events to the wells, and near cessation of activity after the injection well was shut down indicate a causal relationship between the high pre-sure fluid injection and seismic activity. In August 1972 a second well was hydrofractured and subsequently used as the injection well of the salt recovery operation. However, only a few events occurred near the well used in 1972. The hydrofracture and pressure histories of the 1971 and 1972 injection wells were nearly identical. The two wells, 0.5 km apart, are 0.5 km deep and both bottom near the Clarendon-Linden fault, a major feature which extends for at least 150 km. The 1972 well was hydrofractured near the middle of the salt layer, whereas that in 1971 was hydrofractured near its base. The water loss in 1971 was appreciable, but that in 1972 was negligible. The differences in seismic activity and water loss are consistent with the hypothesis that fluids and thus high pore pressures were confined to the salt layer in 1972 but into the fault zone in the rock unit below the salt.

11. The time history of displacement on opposite sides of the fault during the Parkfield, California of June 27, 1966 has been modeled. Data used are ground displacement obtained by double integration of accelerograms recorded at five sites near the southeastern end of rupture. Ground displacement to compare with the data have been computed as if each of these sites were located in an infinite homogeneous space and the rupture were a smoothly propagating ramp. Reasonable agreement is obtained on most horizontal components before the arrival of surface waves. The best fitting model has a well controlled propagation velocity of 2.8 to 3.0 km/sec, but allows any particle velocity on the fault surface greater than 10 cm/sec.

12. Earthquakes are the immediate result of some rupture process, which spreads rapidly in time over a zone in which stress has previously been slowly accumulating. Evidence on the kinematics of this rupture process is available from geological and engineering field studies, from distribution of the first motions radiated by the source, and from our understanding of large-scale tectonic motions. Such studies all indicate that the earthquake mechanism commonly involves shear failure across a planar fault surface.

Motions at and near an earthquake source are investigated theoretically and numerically. The source is modeled by a crack across which the shear stress is dropped to some constant times the normal stress: the crack nucleates from a point, and then grows steadily as an ellipse with fixed eccentricity. The solutions allow rapid computation of the accelerations radiated, at all points in space and time. At about 1 km from the fault surface, but 10 km from the point of initial rupture, accelerations reach up to about 1/2 g (per 100 bars of stress drop) as the rupture front passes nearby. The description of earthquake source motions satisfies both the kinematic and dynamic requirements of shear failure on a plane fault surface.

13. Recent work casting much light on the actual physical processes taking place at an earthquake hypocenter has been supported, in part, by this contract. Scholz, Sykes, and Aggarwal have developed the rock dilatancy-water diffusion model of the earthquake source region from a diverse set of data, some of which was obtained from the seismograph network around the Blue Mountain Lake earthquake swarm. This dilatancy model goes far toward explaining the nature of an earthquake source before, during and after failure. They show that precursory effects such as crustal movement, changes in seismic velocities, tilts, fluid pressure, electrical and magnetic fields, random emission, and frequency and distribution by magnitude of small local shocks occur before many, perhaps all, shallow earthquakes and demonstrate that these heretofore unrelated premonitory effects occur at a characteristic time before the earthquake which is directly relatable to the magnitude of the event. This physical basis promises to lead us soon to quantitative deterministic earthquake prediction.

Briefly, the model describes a sequence of events that occur before failure. As the ambient stress rises in the source region due to tectonic forces the rock undergoes an inelastic increase in volume produced by cracks forming and propagating. This phenomenon is called dilatancy and can occur at stresses as low as half the breaking strength of the rock. While cracks are forming and for some time after, the rock will be undersaturated because of the finite time it takes water to diffuse in to fill the new cracks. The undersaturation of the rocks causes the propagation velocity of P waves to decrease, as well as several other observed premonitory effects. In addition, the undersaturation decreases the pore pressure in the dilatant region and hence increases the effective stress, a phenomenon called dilatancy hardening, which actually strengthens the rock, inhibiting rupture despite a continued rise in ambient stress. As fluid flows into the dilatant region the new cracks fill and the rock becomes more saturated. The pore pressure cannot begin to rise until the rock is wholly saturated but when it does, it lowers the effective stress, weakening the rock. Since the tectonic stress continues to rise during the dilatant period, the rising pore pressure triggers the earthquake just as it does through fluid injection or reservoir filling. Thus dilatancy first delays the earthquake by reducing fluid pressure on the fault, then triggers it when the pore pressure is recovered. The time scale of this sequence of events is controlled by the diffusion of fluid and consequently depends on the size of the dilatnat region, relating the duration of the premonitory stages to the magnitude of the earthquake.

This theory, in addition to promising exciting advances in earthquake prediction, provides the first comprehensive physical description of the

nature of the earthquake source region. To date, the dilatancy model seems to apply best to intraplate events where the dominant stress is compressional. Extending the model to other stress regimes is an active area of research.

14. Five accelerograms recorded near the southeast end of the rupture of June 27, 1966 earthquake at Parkfield, California have been doubly integrated to give ground displacement records. Theoretical ground displacements were calculated for comparison based on a smoothly propagating ramp in a homogeneous half space. The theoretical displacement agreed reasonably well with the observations of horizontal motion before the arrival of the surface waves, with a best fitting propagation velocity of 2.8 to 3.0 km/sec. A paper describing this modelling of an earthquake source is in press with the Bulletin of the Seismological Society of America.

15. In advancing our understanding of possible driving mechanisms of plate tectonics, Sykes and Sbar (1973, 1974) have considered the focal mechanism of intraplate earthquakes. Most intraplate earthquakes were interpreted to be of thrusting mechanisms, suggesting horizontal compression as the dominant component of stress. In fact, Sbar and Sykes (1973, 1974) have suggested much of eastern North America is in a state of high horizontal compressive stress. We have recently completed a detailed study of one intraplate earthquake in the eastern United States. The principal results are that an accelerogram obtained at Blue Mountain Lake is remarkable for the simplicity of its S-wave pulse. This is due to 1) a nearly complete absence of scattering and reflectins as second arrivals on the accelerogram and 2) a very elementary earthquake source. The earthquake identified with this accelerogram had a magnitude $m_b = 2.2$ and a hypocentral distance of about 1 km from the accelerometer. Analysis of the S-wave indicates the earthquake had a moment of 5. to 6.3×10^{18} dyne-cm, and a source radius of 20 to 40 m. When the accelerogram is integrated to obtain displacement, there is a step offset of about 5 microns associated with a near field component of the S-wave pulse. The S-wave, including the step offset, can be matched in remarkable detail by a dislocation model.

16. We have made a systematic comparison of motions on a half space near a fault with those which would occur in a whole space if the surface were absent. We use the Green's function for a half space given by Johnson (1974). Use of this Green's function allows four major surface effects to be studied: the amplification of all waves; the phase shift of SV waves incident at angles more grazing than critical; the SP-phase which is a P-wave converted from an SV wave incident at the critical angle; and Rayleigh waves. Our objective is a critical evaluation of the assumption, used frequently in dislocation modeling, that the free surface can be reasonably accounted for by doubling the whole space amplitude (eg. Kanamori, 1972; Trifunac, 1974; Trifunac and Udwadia, 1973; Anderson, 1974).

In doing this, we have developed a practical way of computing displacements on the surface of a half space as a two step process. The first step is calculating and storing the Green's function for a given station for several points on the fault; and the second step is convolving with the source time function. This method can be faster than the corresponding whole space calculations (which recompute the Green's function) when several models are tried for the same geometry, as in a studying a particular ac-

celerogram record. This method also gives a clear idea of what frequencies are significant in a given record.

The results are that motions on the surface of a half space may be approximated by doubling the amplitude of motion in an infinite space when angles of incidence are less than 30 degrees. For greater angles of incidence, the faulting parameters derived from a whole space model in this manner are potentially somewhat misleading. The P- and SV-waves from a point source in the half space can generally be obtained from the whole space counterparts by applying the appropriate plane wave surface correction. The SV-waves for angles somewhat greater than critical cannot be derived in this way, neither can the AP-phase of the Rayleigh wave.

Line - Item 0001f

1. A paper entitled "Three-dimensional seismic ray tracing in a laterally heterogeneous spherical earth" by Klaus H. Jacob was publsihed in the Journal of Geophysical Research. Recent seismological studies suggest lateral inhomogeneities in P and S velocities of the mantle that are associated with slabs of mobile lithosphere descending into the mantle beneath island arcs. In special cases, travel times of P traversing such zones can differ by as much as 5 sec and of S by up to 10 sec from standard travel times. In addition, such zones are characterized by relatively low attenuation of S-wave energy compared with high attenuation in a broad zone on the landward side of the active volcanoes. To explain the observed anomalous travel times and attenuation phenomena, it is necessary to trace the path of body waves through laterally heterogeneous earth models. The technique of ray tracing developed here uses Fermat's principle to obtain the differential equation of a ray in spherical coordinates. The position, direction, and travel time of the seismic wave front at any point along the curved ray path are obtained by numerical integration of the differential equation for an assumed three-dimensional, continuous velocity distribution. The problem of representing a realistic three-dimensional velocity structure in the earth is solved in a way that is especially suitable for use on computers. Some examples for rays traversing an island-arc structure are presented. The implications of this method of tracing rays in a laterally heterogeneous earth are discussed with respect to seismic travel-time studies, interpretation of residuals in terms of tectonic heterogeneities, source bias, and the precise location of earthquakes and nuclear explosions; $dT/d\Delta$ measurements from large seismic arrays and their inversion to obtain details of the velocity structure in the upper mantle are also discussed.

2. A paper entitled "Seismic waves reflected from velocity gradient anomalies within the Earth's upper mantle" by Paul G. Richards has been submitted to Zeitschrift für Geophysik. Classical Thomson-Haskell methods have recently been extended, to obtain the asymptotic wave solution in a stratified elastic medium which has both first and second order discontinuities in the elastic parameters. These methods are used here in a discussion of the observed precursors to seismic waves P′P′. The frequency-dependent reflection coefficient R (= reflected/incident displacement amplitudes) is calculated for several models of transition regions in the

Earth's mantle. To generate observable precursors to P´P´, by reflection from horizontal layering within the mantle, the thickness L of the region of transition is shown to be much smaller than has generally been supposed. This result follows from the rapid decrease in R as the transition thickness increases from zero to one wavelength. For example, R(1 second) > 2 1/2% only if L < 4 km, even in cases of 10% total changes in velocity.

3. The elastic radiation from an earthquake, modelled by dynamic cracking has been calculated. The elastic wave solution for a plane stress, has now been programmed in an efficient way for the IBM 1130. The output from several computer runs has shown that this mode of energy release seems to require rupture velocities which are of the order of the Rayleigh speed.

4. The excitation of normal modes by a moving source has been studied. A dynamic reciprocity theorem has been proved, which permits the calculation of normal mode excitation in the Earth by a moving double couple. The axial symmetry of a stationary source is lost, and the solution involves summation over axial order numbers.

5. Teleseismic determinations of body-wave (P, S) spectra, interpreted in terms of the Brune (1970) seismic source model, are used to estimate the parameters seismic moment (M_o) and source dimension (r) for three large, shallow, strike-slip earthquakes occurring on nearly vertical fault planes and for which the same parameters can be determined from field (F) data. These earthquakes are (1) the Borrego Mountain, California, earthquake (April 9, 1968) for which [$\bar{M}_o$(P) = 10., $\bar{M}_o$(S) = 6.6, and $\bar{M}_o$(F) = 3.6] x 10^{25} dyne-cms and [$\bar{r}$(P) = 13, $\bar{r}$(S) = 21, and L/2(F) = 17] kms; (2) the Mudurnu Valley, Turkey, earthquake (July 22, 1967) for which [$\bar{M}_o$(P) = 9.1, $\bar{M}_o$(S) = 8.5, and $\bar{M}_o$(F) = 7.2] x 10^{26} dyne-cms, and [$\bar{r}$(P) = 38, $\bar{r}$(S) = 41, and L/2(F) = 40] kms; and (3) the Dasht-e-Bayaz, Iran, earthquake (August 31, 1968) for which [$\bar{M}_o$(P) = 4.8, $\bar{M}_o$(S) = 8.6, and $\bar{M}_o$(F) = 18] x 10^{26} dyne-cms, and [$\bar{r}$(P) = 47, $\bar{r}$(S) = 42, and L/2(F) = 40] kms. The Brune (1970) model is well-calibrated with respect to the determination of these parameters for the earthquake considered. A minimum estimate for the radiated energy can be expressed in terms of M_o and r; this estimate is low by a factor of 3-10 with respect to the estimate obtained from energy-magnitude relations for these three earthquakes. The stress drops of these events are of the order of 10 bars.

6. Archambeau's source theory (Rev. Geophys., 1968) predicts a distinct peak in the displacement amplitude spectrum of body waves radiated into the far field. Assuming that earthquakes may alternatively be described by dislocation theory, this peak in the spectrum can occur only if either (1) different parts of the fault, but on the same side of the fault, slip in opposite directions, or (2) the fault slips back after exceeding the maximum displacement. Data at the present time do not provide strong evidence for a peak in the displacement spectrum. The peak in Archambeau's spectrum may be caused by the absence of frictional damping in his model.

7. Rayleigh waves have been propagated into wedges by solving the equations of motion numerically. The method used is a hybrid between the finite difference and finite element methods. It is based on the fact that the usual finite difference formulae are equivalent to those obtained from linear finite elements over a triangulated rectangular net. The finite element method is then used to derive new difference formulae at points not surrounded by elements such as, for example, the apex of a wedge. Computer generated movies show the propagation of the waves around the corner, the reflected waves, and the radiation of body waves from the corner.

8. An approximate source dislocation theory (Brune, 1970) predicting the shape of the body wave spectra is critically examined. The pattern of dislocation amplitudes after the earthquake, calculated from the strong-motion accelerogram, is compared with the documented offsets along the surface fracture (Buwalda, unpublished field notes). The agreement between these two independent methods of measurement is good, suggesting that the above theory is an adequate first approximation for the spectra of body waves.

The stress variations along the fault indicate two areas of major stress concentration located near the northwestern and southeastern ends of dislocation. The stress-drops for various events varied from about ten to several hundred bars.

9. The seismic surface wave magnitude is dependent on the transmission and reflection of the surface waves at the continental margins. Love wave transmission and reflection is investigated theoretically. The transmission and reflection coefficients are found to be strongly dependent on the period of the Love waves. In models of a continental margin the outgoing Love wave has for some periods a larger amplitude than the incoming Love wave. A simple explanation is, that a Love wave to contain the same energy density in a less rigid medium will have to have larger amplitudes than a Love wave in a more rigid medium.

The Love wave transmission and reflection dependence on the angle of incidence is qualitatively similar to the dependence found for propagating rays of elastic waves.

The method views the Love wave as a super-position of SH rays, that are constructively interfering in a layer, and inhomogeneous SH rays propagating horizontally in the half space below.

The vertical boundary conditions in the continental margin model are satisfied exactly. The horizontal boundary conditions will give rise to diffracted waves, dependent on period, model and angle of incidence. Since

most of the energy is in the Love waves the coupling of the diffracted waves into the Love waves is considered to be minor.

11. Attenuation plays an important role in the transmission of body phases through island arc and trench regions and through the low velocity zone. Recent theoretical work on attenuation by Strick and others predicts that the pulse or wavelet, in addition to being broadened and depleted of high-frequency components as expected, is also delayed. This theoretically predicted delay is not insignificant (amounting to as much as 20% of the travel time for media such as plexi-glass) and, if true, could require important correction of travel time tables as well as modification of existing models of the lithosphere in island arc regions.

The reality of this theoretical delay is being investigated numerically. It has been found to depend, paradoxically, on the behavior of the attenuation model at the very highest frequencies - frequencies for which the transmission of energy is negligible. This baffling fact is a direct result of the formal constraint that the body-wave arrival be causal. Since attenuation is, at some level, related to thermal dissapation which can propagate -- formally at least -- with infinite velocity, we are investigating the possibility of permitting some midly non-causal propagation to remove the intuitively objectionable predicted delay.

12. A combined theoretical and observational study of the refraction of Love waves employs a method developed for calculating reflection and transmission of inhomogeneous SH waves. The components of the Love waves in the appropriate medial are determined to obtain the transmission and reflection coefficients for Love waves. This technique agrees excellently with previous finite element results. A typical calculation takes .02 seconds on an IBM 360, Model 91, which compares most favorably with the 10 to 20 minutes required for the equivalent finite element computation. Love-wave transmission and reflection has been numerically investigated in models of a continental margin. The boundary conditions are satisfied exactly at the interface between the oceanic and the continental model. Diffracted waves for the problems investigated can be considered to have a minor influence, since most of the energy is in the transmitted or reflected Love waves.

Preliminary observations of the transmitted Love wave amplitudes have been made at the ocean bottom siesmic station, OBS, and the nearby seismic station Byerly, BKS, in Berkeley, California. The transmitted amplitudes are strongly dependent on period. For propagation from the ocean to the continent, the transmitted amplitudes are largest for the shortest of the observed periods, 20 sec. For propagation from the continent to the ocean, the transmitted amplitudes are largest for the longest of the observed period, 60 sec.

To explain the observed trends in the data it is found necessary to use models that have a low-velocity layer in the mantle under the ocean.

A very large change in amplitude at the crossing of the continental margin as well as the transmission dependence on angle incidence is presently under investigation.

13. Richards has investigated a dynamic model of earthquake faulting to help quantify the stress drop associated with an earthquake. His model nucleates at the fault motion at a point and allows the rupture to spread. When the rupture zone grows over a large part of the fault surface, the particle velocities become proportional to the stress drop. The proportionality constant may vary for a variety of earth material. Westerly granite, for example, gives 60 cm/sec particle velocity for each 100 bars of stress drop. A paper describing this work is in press with the Journal of Applied Physics.

14. A major problem in the development of a theory for seismic body waves lies in the fact that P and S waves do not propagate independently in a heterogeneous medium like the earth. Richards has approached this problem in terms of potentials for P and S waves, and it has been found possible to display a coupling coefficient between P and SV motion. The method permits many known solutions for scalar waves in the heterogeneous media to be adapted to the study of P waves in seismology. A manuscript describing this potential method is nearing completion, with submission to the Bull. Seis. Soc. of Amer. expected before the end of September.

15. Love wave transmission is studied numerically for propagation from one layered structure into another layered structure. By a new method of approximation the transmission coefficients can be computed for propagation directions differing from normal incidence. The method treats the steady state case. A Love mode is viewed as a superposition of propagating plane SH waves in those surface layers that have S-velocity smaller than the phase velocity, and inhomogeneous plane SH waves in layers having S-velocity larger than the phase velocity, notably in the lower halfspace of the layered structure. The term inhomogeneous plane waves is introduced in this study in agreement with the notation for electromagnetic waves that are solutions to the wave equations; they propagate in one direction in space and fall off in a direction perpendicular to it. The inhomogeneous plane waves are reflected and transmitted at a boundary just as are propagating (homogeneous) plane waves. The method is based on satisfying all boundary conditions on the vertical interface between two layered structures and computing the coupling between the interface stress-displacement field and the transmitted Love modes. The computations are done rapidly on a computer. The results of the present approximation method compare favorably with finite element computations reported in the literature, which require far more computer time.

Love wave amplitude observations were made at the seismic stations OBS on the ocean bottom northwest of San Francisco and BKS in Berkeley. Amplitudes and corresponding periods were read visually from the seismograms, and a few of these readings are supported by Fourier analysis results. The average trends of the observations are an increase of BKS/OBS amplitude ratio with decreasing period in the interval 60-20 seconds, and almost no dependence on angle of incidence between 0 and 60 degrees. These trends are common for propagation from the ocean to the continent and vice versa.

By comparison of the observations with computations for different layered structures a physical explanation is given of the observed trends. The amplitude vs. depth curves for Love waves in an oceanic structure have different shapes than those in a continental structure. The fundamental mode in the oceanic structure has large amplitudes in the low velocity channel, while in the

continental structure it has the largest amplitudes at the surface. The difference between the amplitude vs. depth curves of the two fundamental modes becomes larger as the periods become shorter in the interval of interest, 60 to 20 seconds. At the continental margin energy is transmitted up or down. For periods shorter than approximately 25-30 seconds the first higher modes with large amplitudes in the low velocity zone play an important role in the transfer of energy. For transmission from the continent to the ocean, the first higher mode also has a surface amplitude larger than that of the fundamental mode. For the periods between 20 and 30 seconds there is a significant amount of mode conversion at a continental margin. The horizontal transmission of energy cannot be evaluated separately from the vertical transfer of energy caused by the different amplitude-depth curves of the ocean and the continent.

The suggestion in the literature that the transmission of energy is the same for propagation back and forth between a normal mode in one structure and a normal mode in another structure is verified. Reflections can be computed by the method of this paper. The reflection coefficients computed for a few suggested models are close to zero except for angles of incidence close to or beyond critical, which is beyond 60 degrees for these models. Beyond 60 degrees the simple transmission in the form of normal mode coupling is probably complicated by surface waves horizontally refracted along the continental margin.

16. A new technique has been developed for simultaneously measuring the average, regional phase velocity of two or more surface wave modes, even if they travel with the same group velocity. Many observations are required over paths of varying length with earthquake sources of known focal mechanism. The phase of the signal observed at each station can be predicted if the initial phase of the source and the phase velocity and relative amplitude of each mode is known. The square of the difference between the observed phase and the predicted phase is summed over all paths for a set of trial phase velocities. The trial velocities which give the minimum sum correspond to the average phase velocity of each mode.

By applying this technique to Love wave data from the east Pacific, the dispersion of the first higher Love mode was measured for the first time in an oceanic area. The phase velocity of the fundamental mode was found to increase with increasing age of the sea floor, probably as a result of the cooling of the oceanic lithosphere. The region was found to be anisotropic for Love wave propagation, with the fastest velocities roughly perpendicular to the ridge. The degree of anisotropy appears to increase with increasing period. This has been submitted to the Bulletin of the Seismological Soceity of America.

17. A study is currently in progress to test the validity of various models of the core-mantle boundary using synthetic seismograms. The Langer method of frequency domain calculations (Richards, 1975) has distinct advantages over other methods in describing the effects of earth structure on waves propagating through the earth. The method is uniformly asymptotic in frequency, as opposed to virtually all other approximating methods which are non-uniform and fail at turning points. In addition, for a ray with a turning point near a discontinuity in the earth, the Langer approach corrects the

reflection and transmission coefficients for dependence on frequency, radius or curvature of a discontinuity and the effect of earth structure near the discontinuity. Indeed, the observation of multiple core phases at distances beyond the range predicted by classical ray theory for currently acceptable earth models can now be explained in terms of tunnelling phenomenon (Richards, 1973, 1975) in which rays with turning points just above the core-mantle boundary can leak energy into the earth's core.

The Langer approach is currently being applied to the synthesis of theoretical seismograms of SKS and SKKS and recorded on long period instruments. The method also easily accounts for diffracted energy associated with SKS in a body wave called $SP_{diff}KS$ (King and Muller, 1975). The behavior of the long period content of these body waves should deviate from classical ray theory. The extent and sensitivity of this deviation for various earth models will be investigated. The comparison of synthesized seismograms with data from WWSSN and other seismic stations will serve as a guide to the validity of various earth models at the core-mantle transition zone.

Line - Item 0001g

1. The study of anomalous, intraplate events in the eastern Himalayas has succeeded in clarifying many of their puzzling aspects.

The region under consideration, defined by the Conference of the Committee on Disarmament (CCD) (1972) report, ranges from 92° to 100° east longitude and from 27° to 34° north latitude. This area occupies a region of the eastern Himalayas where the Great Boundary Fault, Main Thrust Fault and the Indus Suture Zone converge toward an intersection with the northern extension of the Andaman Trench and the Ninety-East Ridge. In spite of the complex tectonic setting, the orientation of the horizontal projection of the maximum compressive stress component appears to be rather uniform throughout this limited region.

All seismic events that occurred in this area are reported in the Preliminary Determination of Epicenters (PDE) published by the National Oceanic and Atmospheric Administration (NOAA). The authors of the CCD report have assigned surface wave magnitudes (M_s) to many of these events, and comparing these surface wave magnitudes to reported PDE body wave magnitudes they have grouped these events into three categories: 1) Type I events, those earthquakes that fall clearly in the earthquake population on an M_s-m_b plot. 2) Type II events, those earthquakes that are statistically indistinguishable from the explosion population on an M_s-m_b plot, and 3) Type III events, those earthquakes that fall in the Central Asian explosion population on an M_s-m_b plot. These three regions of the M_s-m_b plot are defined as:

I: $M_s > m_b - 1.0$

II: $m_b - 1.0 > M_s > m_b - 1.5$

III: $M_s < m_b - 1.5$

and are separated by dashed lines in Figures 1 and 2. Figure 1 is an M_s-m_b

plot using the M_s values computed by the authors of the CCD report. The m_b values used in this plot, the same as those of the CCD report, are taken directly from the PDE reports with no further consideration of station location or distribution taken into account.

The formulation used in the determination of body-wave magnitudes reported in the PDE was changed on 31 October 1966, and hence two different methods of m_b computation are included in Figure 1. The two formulas yield slightly different values of body-wave magnitude. To remove the inconsistency m_b has been recomputed for all the events before 31 October 1966 using the new formula.

An additional problem in computing consistent PDE body-wave magnitudes using the Gutenberg and Richter formula results from including observations at stations less than 20° from the epicenter. Evernden (1967) considered some of the problems resulting from using near stations and concluded that body-wave magnitudes overestimated by as much as 1.5 magnitude units frequently occur because of failure to take into account such effects. He cites a Vermont earthquake as a striking example of this problem. Very few stations observed the Vermont event, the most distant being 2017 km. Five computed magnitudes ranged in value from 3.3 to 5.4, the average being 4.7. An earthquake of this magnitude should have been well observed at teleseismic distances, and hence an inconsistency existed. Recomputation of the magnitude using a more reasonable formula for the observed distance range reduced the magntiude to 3.8 or 3.9, removing the apparent inconsistency.

Taking Evernden's results into account, the body-wave magnitudes for the eastern Himalayan events under consideration here were recomputed dropping all magnitude calculations at epicentral distances less than 20°. The results of this further recalculation are shown in Figure 2 with index numbers for those events whose m_b value change from either of the two previous plots shown in slant numerals. This plot should be more consistent than the previous two, and will be the standard used here for definition of anomalous events in this particular region of the eastern Himalayas.

Discussion of changes. There are a few events whose position on the M_s-m_b plot change rather significantly as a result of the recomputation of m_b values. Specifically, event 36 no longer has an m_b, and hence its potential as an anomalous event is unknown. Recomputation of the body-wave magnitude of this event (36) yields an m_b of 4.5, which places it well within the Type I natural earthquake population. Further, the surface-wave magnitude for this event, and others in the same sequence, may well be underestimated. Examination of surface waves generated by these events shows that Love waves are very well developed on several different azimuths, and Love wave amplitudes average three times the Rayleigh wave amplitudes for at least one observing station. Surface-wave magnitudes based on Love wave observations, as well as Rayleigh wave observations, may well improve the M_s-m_b characteristics of these events, and should be considered in any seismic event detection scheme.

Event 73 changed from a Type III event to a Type II event, and event 30 has changed from a Type II event to a Type I event. Earthquakes in the 1968 sequence (most of events 59 through 84) are grouped in closer proximity on the

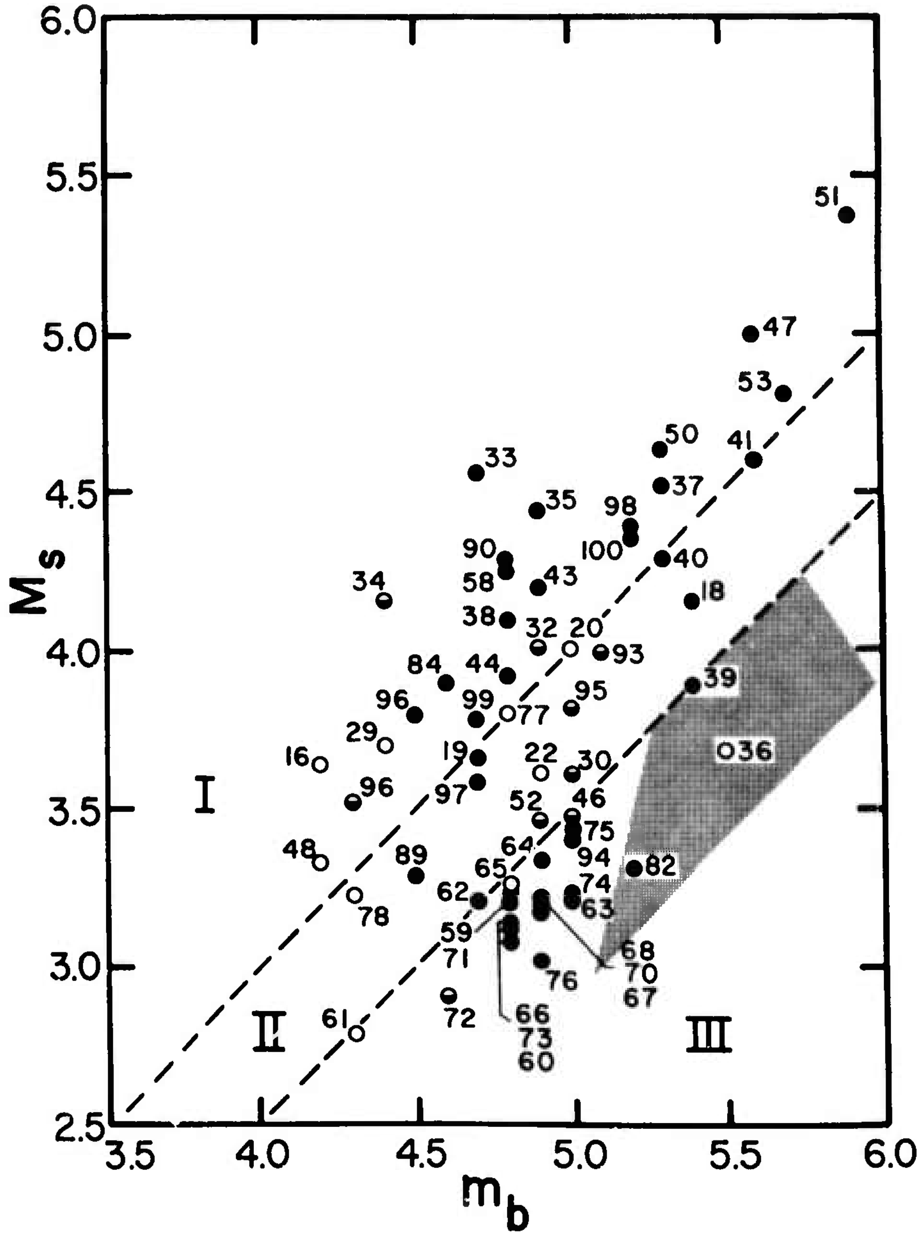

Figure 1 M_s-m_b plot to Tibetan events in the region 27° to 34°N, 92° to 100°E. All events occurred between 1963 and 1972. M_s values were computed by the authors m_b values were taken directly from the Preliminary Determination of Epicenters (PDE). The shaded area contains Marshall & Basham's (1972) observations of underground nuclear explosions in eastern Kazakh and Sinkiang, dashed lines separate the plot into three categories: Type I, the earthquake population; Type II, those events statistically indistinguishable from Type III; and Type III, the explosion-like population. Open circles represent earthquakes with only one station reporting a body-wave magnitude; half-filled circles, earthquakes with two stations reporting; and solid circles, earthquakes with three or more stations reporting. Numbers beside symbols correspond to event number of Table 1.

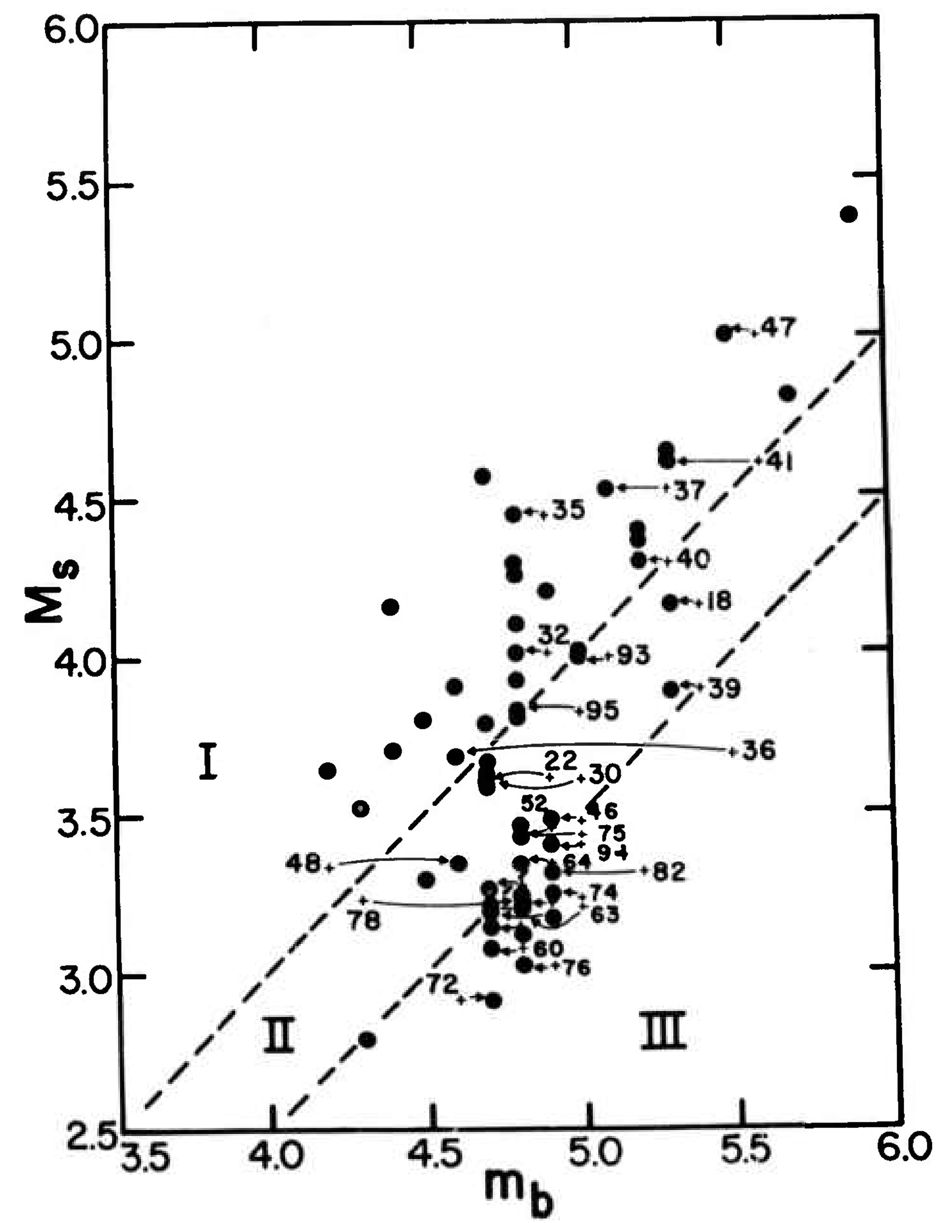

Figure 2 M_s-m_b plot of data in Figure 1 with m_b values recomputed after excluding all observations at epicentral distances less than 20° and considerirg only the m_b value determined by employing the latest m_b formulation. Additional observations made by the authors are included in the revised m_b values. Changes in body wave magnitude from the original PDE values are indicated by arrows, with (+) indicating original magnitude. Note that event 36, the largest anomalous event, is no longer in the explosion population.

revised plot, and with the removal of event 36 as a Type III event, all of the clearly anomalous events (Type III) are contained in this sequence. In general, the improved plot of Figure 2 shows better separation of groups of events than the original plot, thus more clearly defining some of the m_b-M_s problems.

The surface waves generated by the anomalous events share some striking similarities, particularly a predominance of short-period energy with a dominant period generally less than 10 or 15 seconds. Sykes and Sbar (1973) have noted that intraplate earthquakes efficiently generate short-period surface waves, and Tatham (1973) has successfully exploited this observation to examine shallow crustal structure. Tathma suggested that this short-period characteristic of intraplate earthquakes is sufficiently universal to allow these types of events to be used for shallow crustal structure on a nearly global scale.

The surface waves generated by the reliably identified anomalous events, those still remaining outside the natural earthquake population after the m_b recomputations, display the same short-period surface wave characteristics as the intraplate events. Tectonically, this observation could suggest that the earthquakes occurring at a continent-continent collision type of a plate boundary may have more in common with intraplate earthquakes than they do with earthquakes occurring at other types of plate boundaries. Also, the thick crust ($\sim$70 km) in the Tibetan plateau region may further complicate surface-wave magnitude determinations in this area. The fact that earthquakes can occur at rather substantial hypocentral depths could significantly reduce the amplitudes of the generated surface waves. This problem of attenuation with focal depth could be especially acute for these intraplate type events because only the short-period surface waves are created initially, and this is precisely the portion of the surface-wave spectrum that is most severely attenuated, even at rather moderate focal depths. Fortunately, Love wave amplitudes are less strongly attenuated with focal depth than are Rayleigh wave amplitudes, and hence Love waves should be considered in computing surface-wave magnitudes. In addition, the thick crustal section may contribute toward a stronger wave-guide effect than exists in other areas of the world, and thus Love wave development and transmission may be favorably enhanced. The fact that well developed Love waves are observed for many of the natural earthquakes occurring within the area under consideration supports these hypotheses and increases the likelihood that Love wave magnitudes could be useful in the reliable and consistent determination of surface-wave magnitudes.

2. In compiling a tectonic map of the eastern Himalayas, several different published sources were employed. Unfortunately, the region of interest lies near the geographic limits of these previous studies and hence correlations between different investigator's interpretations may not be precise.

The principal reference, Terman's (1974) tectonic map of China and Mongolia, extends southward to and includes the Indus Suture Zone. This map, on a scale of 1:5,000,000, was used as the base in constructing the composite tectonic picture of the region in question. The geology of the Himalayas has been considered by Gansser (1964), with the construction of a regional tectonic map compiled at a scale of 1:10,000,000. Unfortunately, Gansser's geologic control in the eastern Himalayas is rather meager, with the position of the

Main Central Thrust east of Shillong controlled by a single traverse along the Brahmaputra-Tsangpo River. Further, the identification of this fault is less certain in the eastern Himalayas than for the central and western Himalayas. This uncertainty results because the northern block of the Main Central Thrust is of crystalline material and overthrusts and sediments of the lower Himalayas. In the eastern Himalays, however, crystalline rocks often occur on both sides of the thrust, complicating its identification. Thus, the nature of the convergence of the Main Central Thrust and the Indus Suture Zone is somewhat uncertain.

The tectonic setting of the region of the anomalous events, near 30°N, 95°E, is quite complex. In this rather limited area the Great Boundary Fault, Main Central Thrust and the Indus Suture Zone, all major tectonic features trending the entire length of the Himalayas, converge toward an intersection with the northern extension of the Andaman-Burman arc and the northward projection of the Ninety-East Ridge. Thus, this zone represents not only a region where lithospheric plates are converging in a collision situation, but also represents a convergence of plate boundaries which display differing character trends. The region between the Main Central Thrust and the Indus Suture Zone is occupied by a crystalline metamorphic sequence directly north of the thrust, followed by a sequence of Tethyan sediments whose northern limit is the Indus Suture. However, Thakur and Jain (1974) suggest that the zone of Tethyan sediments is absent in the extreme eastern end of the Himalayan chain. This lack of a sedimentary zone sandwiched between more compotent rock could change the style of tectonic deformation that is occurring, and change at least some of the source parameters of earthquakes accompanying the deformation.

The tectonic framework of the Assam region of India has been discussed by Evans (1964) and his map describes the convergence of the eastern Himalayan thrust (Main Boundary Fault) with the Andaman-Burman arc. Further, Evans identifies the Dauki fault, a strike-slip feature with approximately 250 km of lateral offset since mid-Eocene time. More recent motion across this fault, however, suggests that the northern block (Shillong Plateau) is overthrusting toward the south, thus paralleling the thrusting of the overall Himalayan trend. Evans points out (1964, pg. 90) that resurveys following the Shillong earthquake of 1897 showed that the Shillong (northern) block moved about 1.2 meters southward. Also, the nature of thrusting associated with the Andaman-Burman arc may change north of the Dauki fault. Significantly, the nature of the thrust faults north of the eastward projection of the Dauki fault appears to change. Specifically, the Naga thrusts involve shallow, Tertiary sediments in several thrust sheets, whereas deeper-seated faulting may be more dominant to the south. Deep earthquakes defining a Benioff Zone, however, do continue northward from the Andaman-Burman arc, and may define an earlier episode of subduction for that particular portion of lithosphere.

Gansser (1966), in discussing the relation of the Arakan Yoma trend to the Ninety-East Ridge, suggests that the Arakan Yoma line lies to the southeast of the Naga Hills and the associated Naga thrust. The south-western limit of the Naga thrust is defined by the Dauki Fault, and the Naga thrust may thus be an entirely independent tectonic feature with respect to the Andaman-Burman arc and the Arakan Yoma line.

Regional Seismicity. Molnar et al. (1973) and Das and Filson (1975) have examined the tectonics of Asia utilizing seismicity and fault-plane solutions as principal tools. One consistent observation of all the seismicity studies is the low level of activity on peninsular India, and the relatively high level of disperse seismicity north of the Himalayan region. These numerous earthquakes may be related to the high-stress caused by the collision of the Indian plate with the Asian plate. Das and Filson suggest that the high seismicity on the Asian landmass is caused by the interaction of several tectonic blocks separated by diffuse seismic zones, possibly ancient plate boundaries, which define their geographic limits. Within the areal limits of the present study are portions of four of the tectonic blocks defined by Das and Filson. These blocks are generally bounded by pre-Cenozoic fold belts, and for a portion of one boundary, ophiolite sequences are intermixed with mapped pre-Cenozoic thrusting. This particular portion of the boundary between Das and Filson's East China and West China blocks corresponds to the Lung-Men Shan thrusts and Ta-Pa Shan uplift. The southeast Asian block contains the Salween and Mekong fold belts and its northern end appears to be sandwiched between the converging south China block, of which the South China platform is a part, and the Indian plate. The intense deformation where the Salween, Mekong and Yangtze Rivers follow parallel courses in adjacent V-shaped valleys of great depth, offers dramatic geomorphologic expression of such convergence. This zone also places a limit on the eastward extent of the Himalayan trend.

The work of Evans suggests that the pre-Cambrian basement of Assam, outcropping as the Shillong Plateau and Mikir Hills, forms a small tectonic block or microplate. This block is being overthrust from the northwest along the Main Boundary Fault and from the southeast along the Naga Thrust. These opposing thrust zones are terminated to the northeast by overthrusting of crystalline material at the Mishmi thrust. On the northeast extension of this block beneath the Mishmi Thrust are located the epicenters of two great earthquakes with normal faulting mechanisms, one of which is the great Assam earthquake of 1950 (Figure 1).

Consideration of the seismicity suggests that the central Yunnan Basin may also represent a separate block, or microplate. Unlike other structural features of the East China block, some of the mapped thrusts near the eastern boundary of the central Yunnan Basin are dated as Cenozoic. The possibility of small microplates, or blocks, occurring as part of generally large-scale plate boundaries is one way of accomodating the geometric complications at plate boundaries, especially in the case of non-subductable crust of continent/continent collision. Nowroozi (1971) identified several such plates in the foothills of the western Himalayas, and Dewey et al. (1973) defined several microplates in developing a plate tectonic evolution of the Alpine system. These small plates probably have large components of rotational motion, as well as translational motion, and hence focal mechanisms of earthquakes occurring at their boundaries can be quite complex varying drastically from boundary to boundary. In fact, Dewey et al. (1973, pg. 3139) point out that, for the plate boundary between Africa and Europe, there probably never was just a single plate boundary, but rather, at all times, a network of compressional, extensional and transform boundaries. Such complications are reflected for the eastern Himalayas by the widely varying fault-plane solutions determined by Fitch (1970), Ichikawa et al. (1972), Molnar et al. (1973), Rastogi (1973, 1974) and Das and Filson (1975).

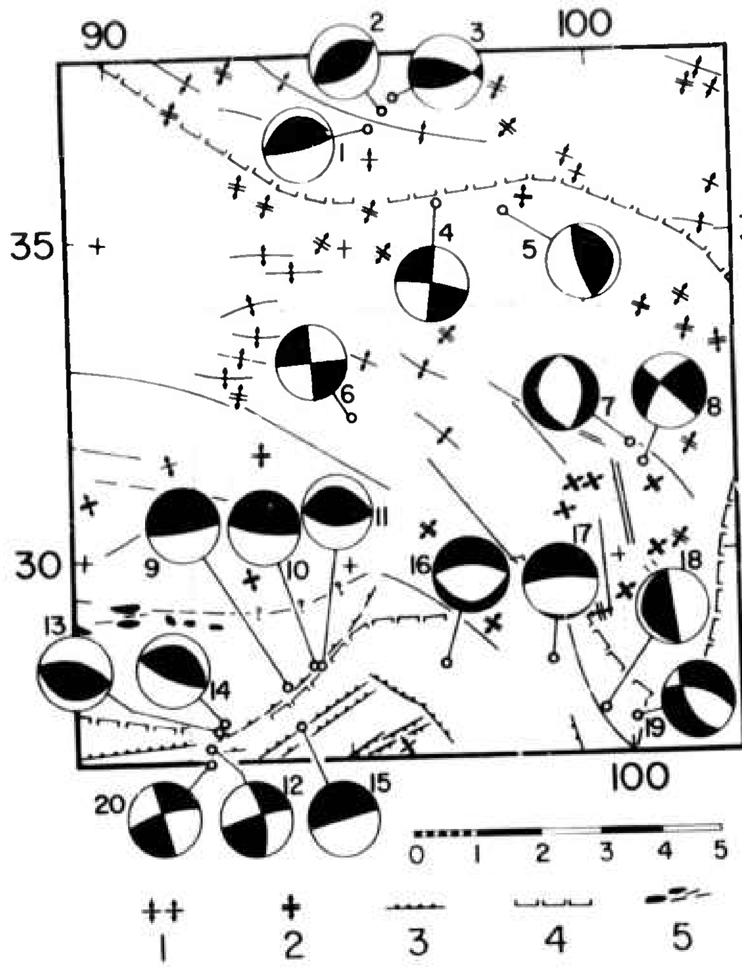

Figure 1 Tectonic features and known focal mechanisms near the area of reported anomalous events. Focal plots are lower hemisphere projections with compressional quadrants darkened. References for focal mechanisms are given in Table I. Numbers on scale bar are 100's of km. Map symbols are as follows: 1-synclines and anticlines; 2-position and trend of tightly compressed anticlines and undetermined number of fold axes; 3-thrust fault, with barbs on overthrust block; 4-approximate contour for 60 km crustal thickness, with barbs toward thinning crust; 5-ophiolites and approximate position of Indus Suture Zone. Dotted box delineates area (92-100°E, 27-34°N) defined by CCD report. Most anomalous events occurred near 95°E, 30°N, where the Indus Suture and Main Central Thrust (northernmost thrust fault) appear to converge. Also, Tethyan sediments, present along most of the Himalayan trend, are absent in this region. Mechanism 17 represents the Great Assam Earthquake of 1950; mechanism 16 a more recent earthquake determined by Molnar et al. (1973). Note that for limited areas between major tectonic and structural elements, the inferred stress field appears to be relatively consistent.

Fault Plane Solutions. Fault-plane solutions within the limited area of consideration for this study are shown in Figure 1. As stated above, fault-plane solutions over the entire eastern Himalayan region vary greatly, and deriving meaningful conclusions with respect to the small area under consideration here may not be possible. Figure 1 shows that north of the Main Boundary Fault, however, the tectonic stress field appears to be rather uniform in nearly north-south compression. A few notable exceptions exist, particularly the normal faulting exhibited by focal mechanisms 16 and 17. Solution 17, a magnitude 8 1/2 earthquake, represents one of the great earthquakes of this century.

To the north, mechanisms 1, 2, and 3 are located within the Tsaidam Basin, a region of Cenozoic deformation and relatively high seismicity. Mechanisms 7 and 8, near the border with the stable south China Platform, may represent complications near that boundary. Event 6 is near the location of most of the anomalous events, and has an aftershock which is statistically indistinguishable from anomalous events.

1968 Sequence of Anomalous Events. The most perplexing anomalous events in this region all occurred in a single sequence over a time span of less than three months, with a lone event occurring about a year later. All of the Type III and most of the Type II events are members of this particular sequence, in which all epicenters are grouped near 95°E, 30°N. The only other event from this area reported in the PDE was an earthquake of m_b 4.8 on 21 December 1973. As of this writing, complete data for the 1973 were not available, so this more recent event cannot be incorporated into the present interpretation.

All of the earthquakes--with one possible exception--that occurred in the particular tectonic setting of this sequence are anomalous. The reported body-wave magnitudes are quite consistent, with as many as five stations reporting m_b values for single events. The only m_b value that might be overestimated is for event 82, and it could conceivably be as small as m_b 5.0. This change would not affect the anomalous nature of the event.

The generally small body-wave magnitudes of the earthquakes in this sequence limit surface wave observations, for most of the events, to a single station. The character of the waveform for all of the events, however, is remarkably consistent. Figure 2 illustrates the arrivals at SHL, approximately 5° from the epicentral region. The amplitude of the vertical component of the Rayleigh wave motion was used in the M_s determinations. Note that the Love wave arrivals on the LPE component have amplitudes about 80% of the vertical component of the fundamental Rayleigh wave. Discrimination based on these Love-wave observations, however, would probably require explosion data from the same area. Such data could be used to define the earthquake and explosion populations on an M_s (Love)-m_b plot. Nevertheless, it does appear that these Love-wave observations could be used as a potential method of discrimination.

Aki and Tsai (1972) found that long-period (> 10 sec) Love-waves generated by nuclear explosions at the Nevada test site can have amplitudes nearly equal to the recorded Rayleigh-wave amplitudes. They observed that the relative amplitudes of explosion-generated Love-waves were quite variable and suggested that a stress release mechanism was reponsible for the Love-wave excitation. They further concluded that a magnitude (or depth) threshold may exist below which strong Love-wave excitation does not occur.

Table I

Data Sources for Figure 1

Solution	Source	Solution	Source
1	M	11	R3
2	I102	12	I34
3	M	13	R1
4	F6	14	R2
5	D24	15	M
6	D5	16	M
7	F13	17	T
8	D27	18	R7
9	F4	19	M
10	F5	20	I6

Data sources for focal mechanism solutions shown in Figure 1. Number following letter refers to author's reference for that particular event. M - Molnar *et al.* (1973); R - Rastogi (1973); I - Ichikawa *et al.* (1972); D - Das and Filson (1975); T - Tandon (1954).

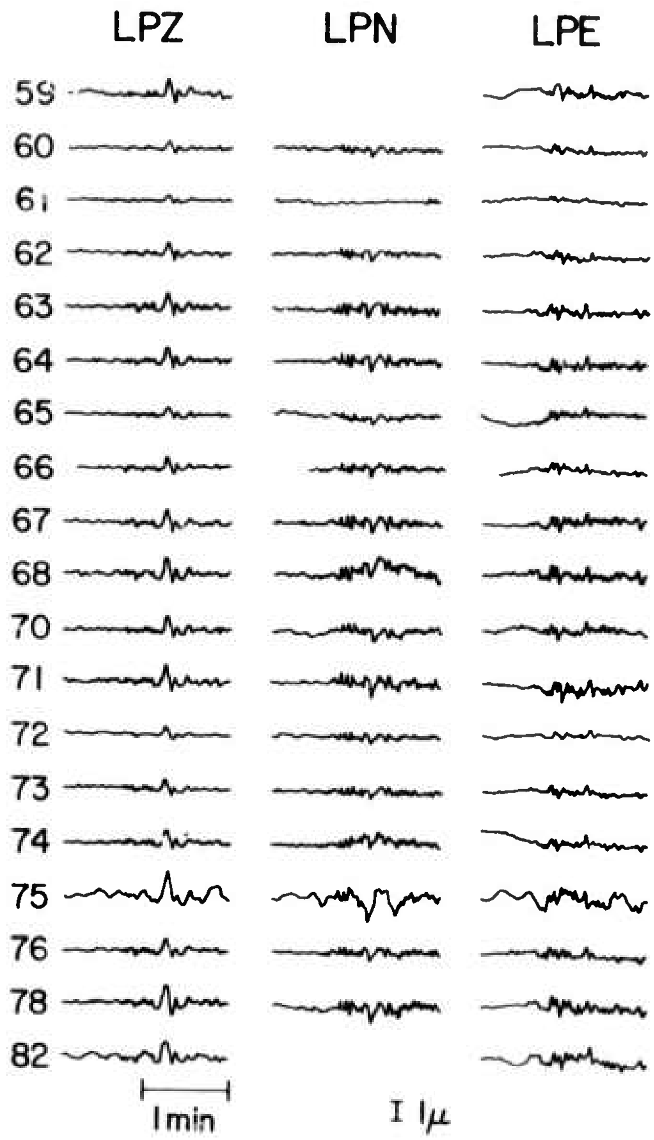

Figure 2 Tracings of SHL long-period recordings of surface-wave arrivals for events in 1968 Sequence in Tibet. Gain of original seismograms is 3000. All of these events occurred near 95°E, 30°N, near the point where the Indus Suture and the Main Central Thrust appear to converge toward a common point at the eastern limit of the Himalayan trend. Note the nearly identical character of all the events, espeically on the vertical component. Love-wave amplitudes on the east-west component are about 80% of the vertical Rayleigh-wave amplitude. Approximately three-fourths of the reported anomalous events are in this sequence.

For the anomalous events in this particular sequence, Love waves are excited almost as efficiently as Rayleigh waves. Further, the relation between the two remains remarkably uniform throughout the entire sequence. Due to the paucity of data from these small magnitude events, methods of discrimination based on focal depth, such as higher-mode generation, would be difficult to apply. It appears, however, that large-amplitude Love-wave observations may provide a potential method of event discrimination for this peculiar seismic sequence.

Event 18 (Type II) $m_b = 5.3$, $M_s = 4.33$. Body-wave magnitudes for this event were reported by only three stations, but they are consistent. The key to discrimination of this event is the rather large amplitude higher-mode Rayleigh waves that are observed. As discussed earlier, the thick crustal section of the Tibet region could efficiently propagate higher-mode Rayleigh waves. Forsyth (1974) has suggested that the degree of higher-modes generated could be used as an effective discriminant, as well as explaining many of the complexities observed in surface-wave recordings of central Asian earthquakes. Panza et al. (1973) have shown that, for at least one focal mechanism and crustal structure, the degree of higher-mode excitation is quite dependent on focal depth. For seismic sources at the surface, the fundamental mode dominates at all periods. As the depth of the source increases, however, higher modes are more efficiently excited than the fundamental mode at many of the frequencies dominant in surface waves traversing continental paths. Further, model dispersion curves show that for a thick continental crust, the first higher mode may have dispersion characteristics similar to the fundamental mode for a normal crust. The fundamental mode may have lower group velocities at longer periods, yielding an apparent inverse dispersion, and thus complicating the interpretation of such surface-wave arrivals.

The total effect of the thick crust is to give the appearance of very complex wave trains. Examples of such wave trains are shown in Figure 3. Event 18 is compared to two Type I events with similar epicentral locations; event 50, a larger earthquake of thrusting mechanism, and event 90, a somewhat smaller earthquake. Arrival times corresponding to particular velocities are indicated on the traces to facilitate interpretation. Note that the first higher mode Rayleigh wave is observed for all three events. For event 50, the maximum amplitude of the first mode is only 20% of the fundamental; for event 90 the first-wave amplitude is 30% of the fundamental; and for event 18, with the anomalously low surface-wave magnitude, the first-mode amplitude is 65% that of the fundamental. These observations are consistent with shallower focal depths for events 50 and 90 than for 18. They strengthen Forsyth's suggestion of employing higher-mode observations as a seismic discriminant. We believe that the large relative amplitude of the first shear mode determines the source of this seismic event as a natural earthquake.

3. A focal mechanism study of the contemporary tectonics of central Asia is being undertaken using data from both WWSSN film chips and information from seismograms recorded in mainland China. The epicentral distribution in this area shows that there is no sharp boundary between the Indian and Eurasian plates as would be expected if the contemporary tectonics were simply the result of the intersection of the two plates. Molnar et al. (1973) proposed that stable blocks within the Eurasian plate may play an important role in the explanation of the tectonics. There presented no quantitative evidence for this proposal.

The quantitative evidence necessary to study this tectonic problem has not been available until the present. Data from the close-in Chinese stations are necessary to determine reliable focal mechanisms for the thrust fault type earthquakes which predominate in the fold belts of central Asia. The WWSSN station distribution does not lend itself to reliable focal mechanisms for this area.

Through the analysis of the combined WWSSN and Chinese data sets, we hope to obtain more accurate orientations for the slip vectors and the directions of the three principal stress axes. The former can be used to define the direction of relative motion between two of the plates and in effect aid in the determination of the plate boundaries. From the stress orientations, we hope to obtain an improved understanding of the relations between the seismicity and the tectonic features.

Twelve strain relief measurements were made at 5 sites on Potsdam Sandstone northeast of the Adirondack Mountains, New York to test Sbar and Sykes (1973) suggestion that the upper crust in a large area of eastern North America is currently in a stage of east-west compression. *In situ* strain was relieved by overcoring, and detected using strain gages bonded to the sandstone at the surface. The average of nine measurements at four sites in the Late Cambrian Keeseville Member of the Potsdam Sandstone indicate that the direction of maximum expansion upon overcoring is N78°W. These nine measurements also indicate that stress can be consistent in orientation over areas of tens of square kilometers. The average of three measurements at one site in the Nicholville Member 11 km from the other four sites indicate a maximum expansion oriented N18°E. Double overcore tests suggest that a sizeable component of the measured strain is residual. We suggest that the residual strain measured in the Nicholville Member may be related to a late Proterozoic (Hadrynian) or early Cambrian stress field.

Line - Item 0001h

1. A comparative event technique was employed to study the rupture process of a large ($M_s \approx 7.0$), strike-slip event on the southern mid-Atlantic ridge. In this technique, small events in the same area as the earthquake of interest are used as reference events. The small earthquakes can be regarded as point sources, so the surface waves observed at distant stations from these events represent the combined effects of source medium on the excitation function, response of the instrument and receiver medium, and any propagation characteristics, such as attenuation or scattering. Any changes observed in the surface wave spectra of a large event compared to the small reference events are due primarily to the finiteness of the source, since the source medium, propagation path and receiver are the same. Using this technique, very accurate determinations of fault-length and rupture velocity are possible with only a few observations. The January 3, 1971, event on the mid-Atlantic ridge had a fault length of 60 km and a rupture velocity of 2.0 km/sec.

2. Ongoing research projects at Lamont-Doherty yield additional insight into the plate-tectonic processes occurring in central Asia. In particular, apparently buoyant features of the ocean basins, such as seamounts and aseismic ridges, resist subduction. This, in turn, leads to distortion of plate boundaries and

possible uplift of the overthrusting plate. Such processes may have been significant in the tectonic evolution of the Assam Valley, on a northern projection of the Ninety-East Rise, and the Hindu-Kush-Karakorum region, on a projection of the Owen-Murray fracture zone. Significantly, stratigraphic evidence suggests that uplift occurred near the Assam area prior to the uplift of the main Himalayan Trend.

3. Projects concerned with seismicity in the western Himalayas have determined focal mechanisms for small and intermediate magnitude earthquakes. Both thrusting and strike-slip have been observed, but in both cases, the orientation of the maximum compressive stress has been consistent with convergence of the Indian and Eurasian plates. Further, investigations into the driving mechanisms of plate tectonics suggest that the forces acting on downgoing slabs at subduction boundaries are an order of magnitude greater than other forces acting on the plates. In addition, drag on the bottom of plates, which resists motion, is stronger under the continents than under the oceans.

4. In advancing our understanding of possible driving mechanisms of plate tectonics, Sykes and Sbar (1973) have considered the focal mechanisms of intraplate earthquakes. Most intraplate earthquakes were interpreted to be of thrusting mechanisms, suggesting horizontal compression as the dominant component of stress. Further, many intraplate earthquakes generate surface curves rich in short-period energy. Such short-period energy has been exploited to examine shallow crustal structure (Tatham, 1975). Some earthquakes, however, appear to be in a transition between a plate boundary and intraplate regime. Such is the case for the eastern Himalayas, where plate boundaries are not well defined. The surface waves, especially Rayleigh waves, generated by anomalous seismic events are similar to intraplate earthquakes in that they are rich in short-period energy. Nevertheless, long-period Love waves are well observed for some of the anomalous events, a characteristic more often associated with events on plate boundaries.

5. The distribution of large shallow earthquakes along subduction boundaries is in serious disagreement with the distribution pattern that might be predicted from a simple model of plate tectonics. That is, along extensive sections of some island arcs large shocks occurred infrequently or not at all during recorded history. Most of these zones of long-term quiescence are nearly coterminous with segments of the margin where zones of seamounts, aseismic ridges or other bathymetric highs of the underthrust slab appear to be interacting with the subduction process. Because of this widespread spatial correlation and because all or nearly all elevated portions of the sea floor have crustal roots, aseismic ridges or other uplifted regions may reveal zones of relative buoyancy within oceanic plates which resist subduction upon collision with an active trench. Thus, in place of the typical subduction process at locations where buoyant zones interact with the subduction process, rigid plate motion may be preserved by a variety of tectonic responses including: arc-polarity reversal, gradual or abrupt shifts in the plate margin, the development of cusps between arcs (as suggested by Vogt, 1973), development of broad zones of deformation, partial subduction (descent to perhaps 50-100 km but no farther) or, possibly, termination of subduction. If our interpretation is valid, then it may be possible to explain in a relatively straightforward manner other modifications of the subduction process such as gaps in the line of active volcanoes, the presence of detached slabs of lithosphere in certain parts of

subduction zones, abrupt changes in strike and dip of the descending lithospheric plate, the absence of intermediate-depth earthquakes in certain locations and the emplacement of ophiolite sequences.

In place of "typical oceanic" lithosphere, therefore, there may exist a broad spectrum of average densities for oceanic lithosphere and the relative buoyancies of the two slabs near the subducting margin appears to be a dominant influence in the development of subduction tectonics and in the locations of great earthquakes.

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Problems Encountered:

None

Action Required by the Government:

None

Future Plans:

Future plans call for the continuation and development of research begun under this contract during the term of a successor contract.

List of Publications Supported by this Contract:

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